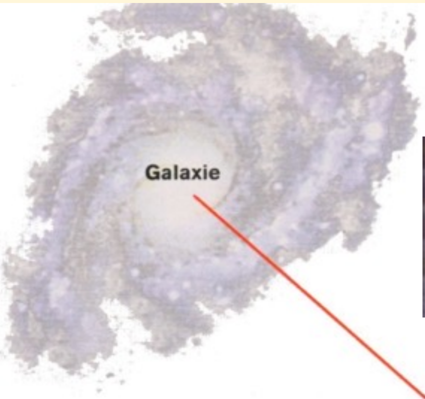
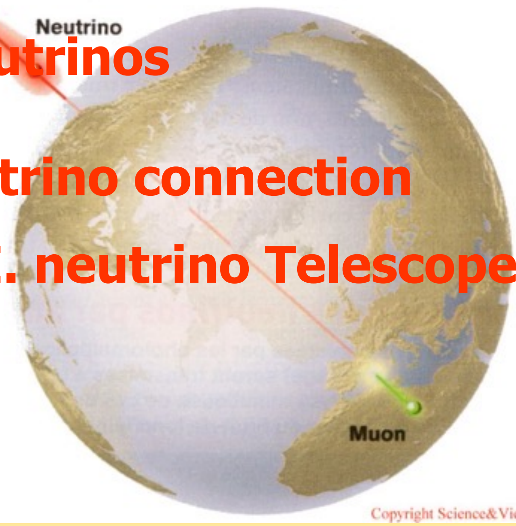
# Searches for High Energy Astrophysical neutrinos: recent results, world-wide perspectives

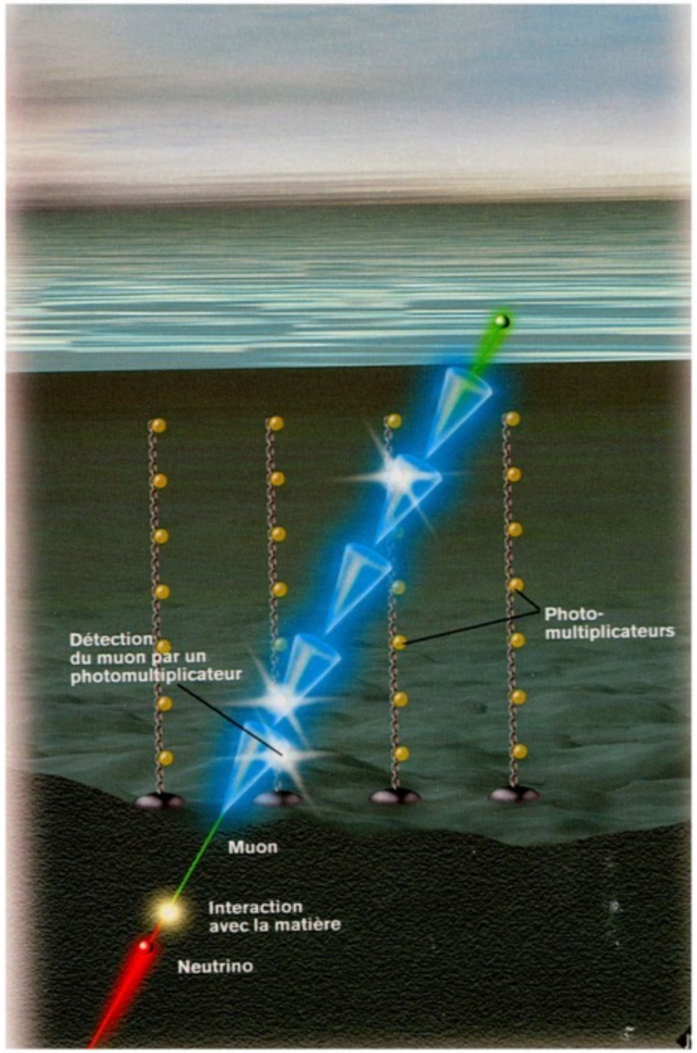



2ND GRAVI-GAMMA WORKSHOP
FROM MULTI-WAVELENGTH TO MULTI-MESSENGER
THE NEW SIGHT OF THE UNIVERSE
23-25 JUNE 2021 - ONLINE EDITION

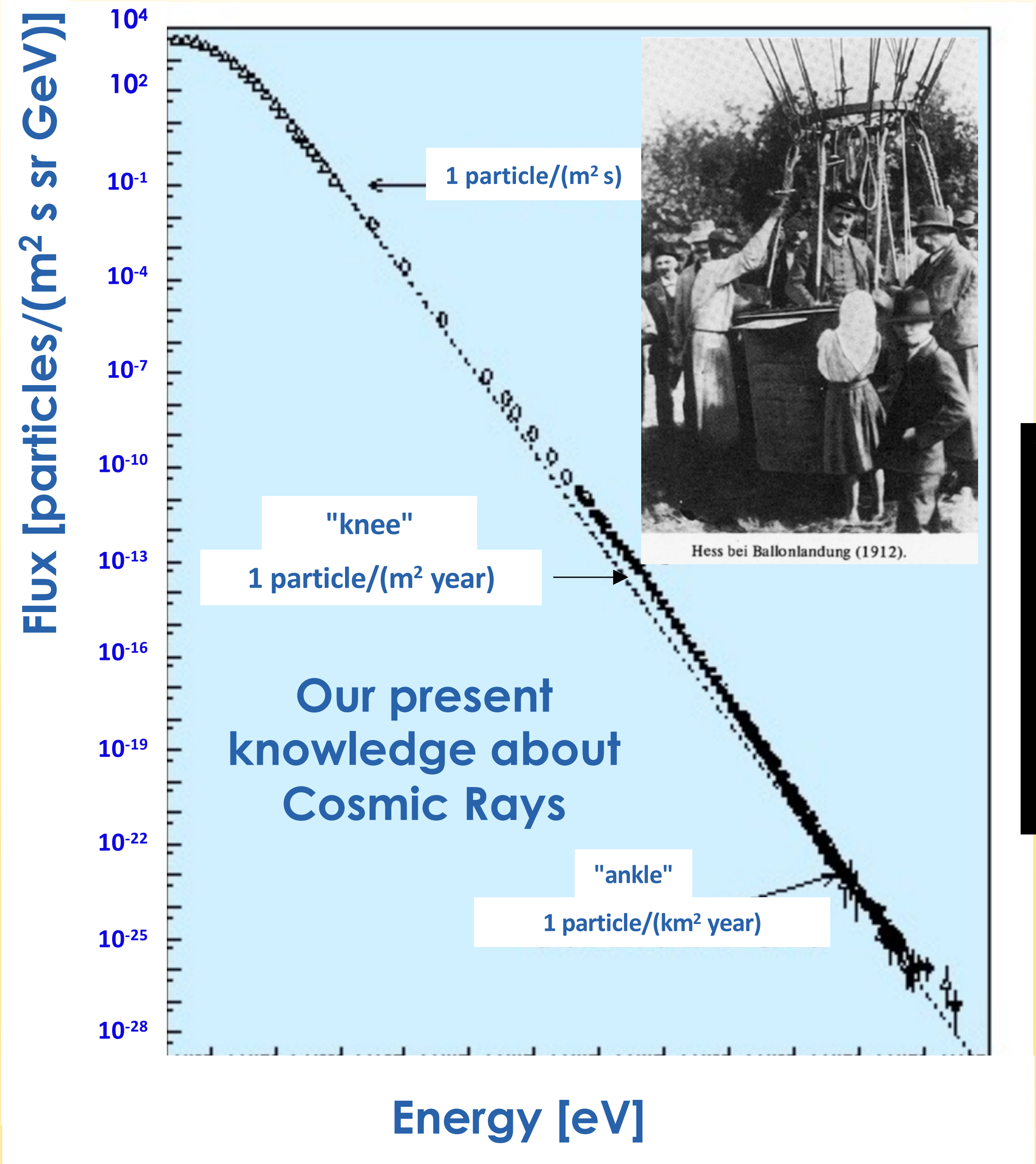
INFN Istituto Nazionale di Fisica Nucleare

- H.E. C.R. Messengers from a remote Universe
- What do we know, what are we investigating
- Astronomy with H.E. neutrinos
- The proton-gamma-neutrino connection
- The effort for future H.E. neutrino Telescopes

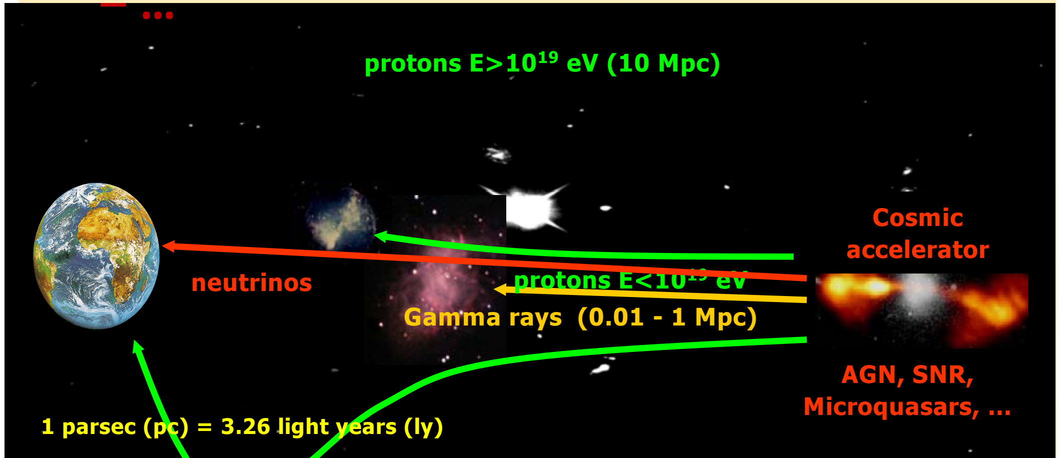


# One century of cosmic rays measurements …




- Observed elementary particles or nuclei carrying a kinetic energy up to $10^{21}$eV (like a tennis ball moving at ~150km/h)
- Many open questions:
  - Where they come from ?
  - Which acceleration mechanism ?
  - …




- UHE astrophysical neutrinos will extend the limits of the "visible" Universe.
- Detection of ν from point-like sources will clarify their “nature”: hadronic/electrom. ??
- Multi-messenger observations

# Motivations for present H.E. neutrino astrophysics

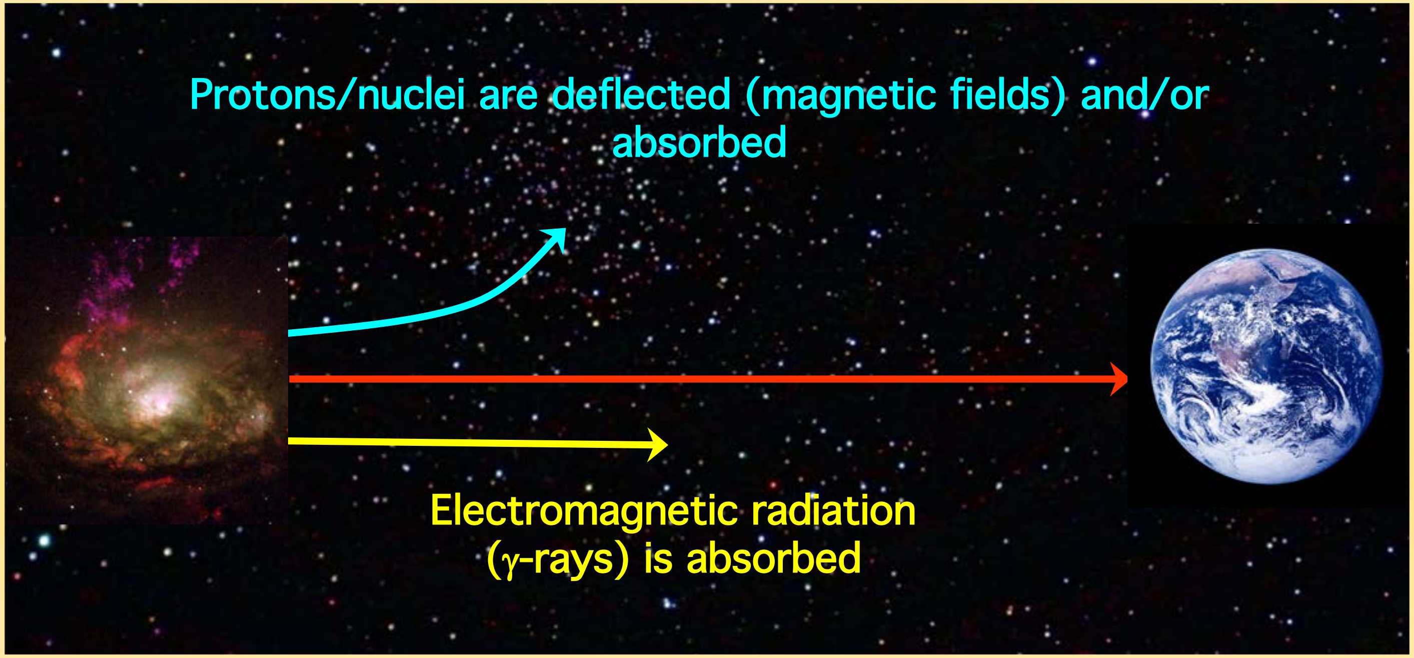
**The U.H.E. Cosmic Rays (>$10^{19}$ eV) require an explanation:**

- **are they proton ? → then they should be "galactic"! → where is their source ?**
- **are they extragalactic protons ? where is their source ? → what about GZK ?**
- **are they heavier nuclei ? where is their source ?**

**Confirmed gamma-ray sources still need to be understood. Do they accelerate hadrons or electrons ? These sources will be the first target of neutrino telescopes observations**:

- search for astrophysical neutrinos in excess to the atmospheric neutrino flux (conventional and prompt);
- search for neutrinos from point-like sources (list of known gamma-ray emitters, steady or transient). Measured $\gamma$-fluxes allow to evaluate the expected amount of $\nu$ events;
- search for neutrinos from Fermi Bubbles and from Galactic Plane;
- Search for neutrino in time/space coincidence with other messenger (radio, gamma, GW, CR, …)

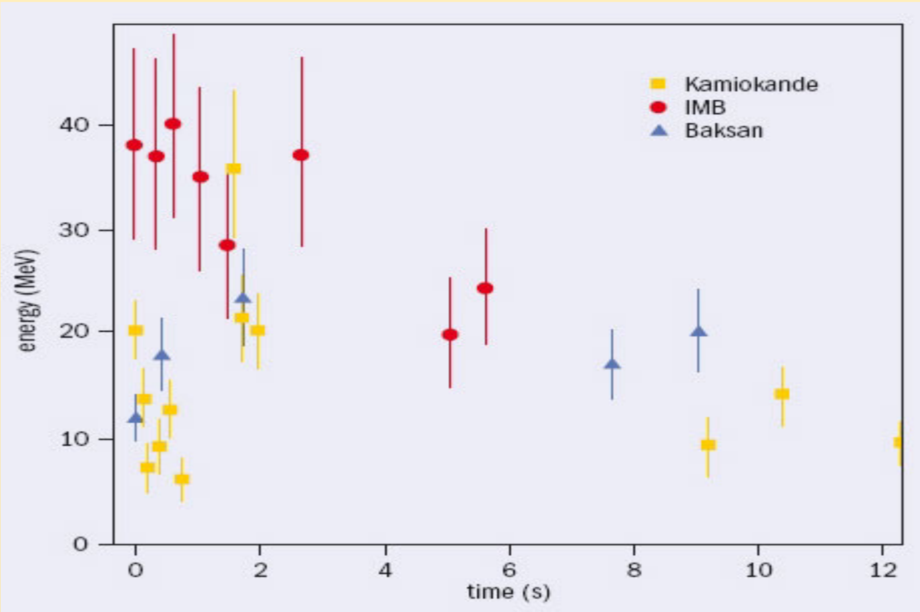
- and let's not forget that neutrinos offer the unique possibility to "look" further away and deeper inside astrophysical objects revealing so far "hidden sources". **The horizon for a Neutrino Telescope is wider.**



# Astrophysical neutrinos from point-like sources

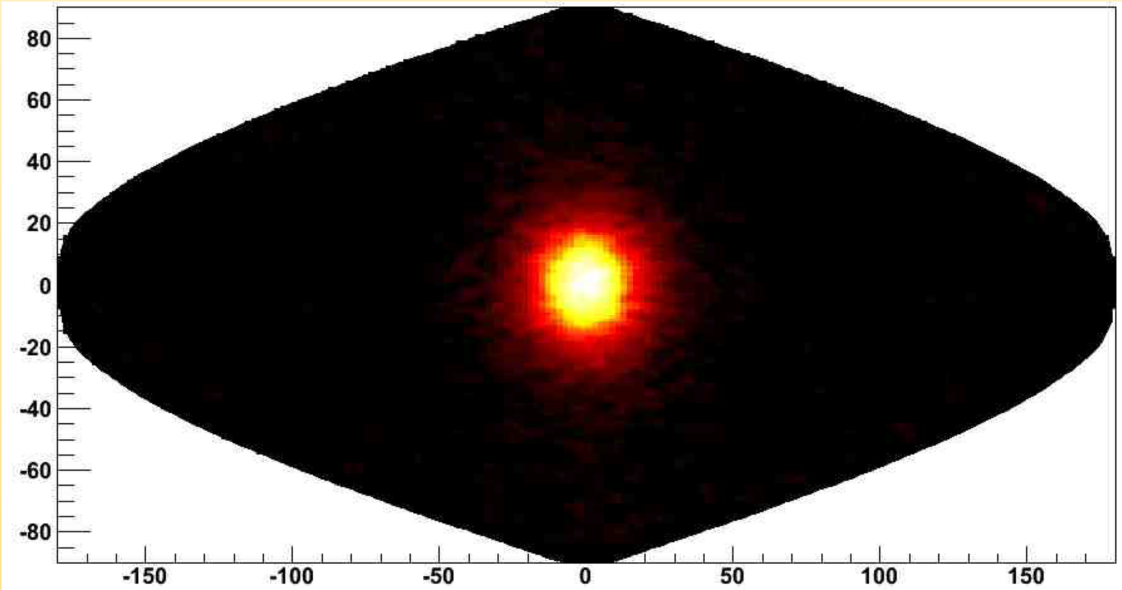
**Neutrino astronomy is already started …. !**

SN1987A neutrino events observed by Kamiokande, IMB and Baksan.



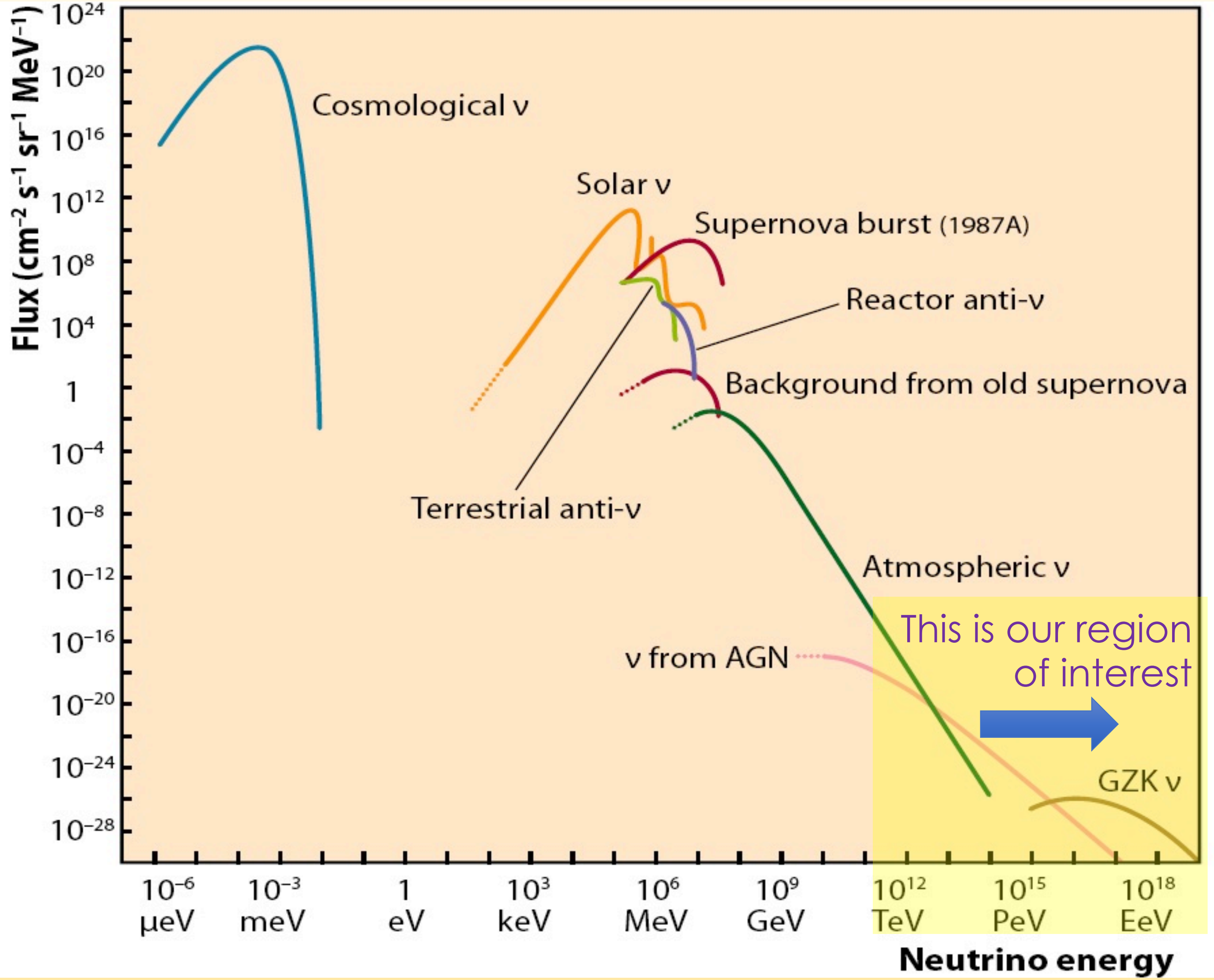

The ν burst lasted about 13 s.

Solar neutrinos measured by SKK (1996-2018)




http://www-sk.icrr.u-tokyo.ac.jp/sk/sk/solar-e.html

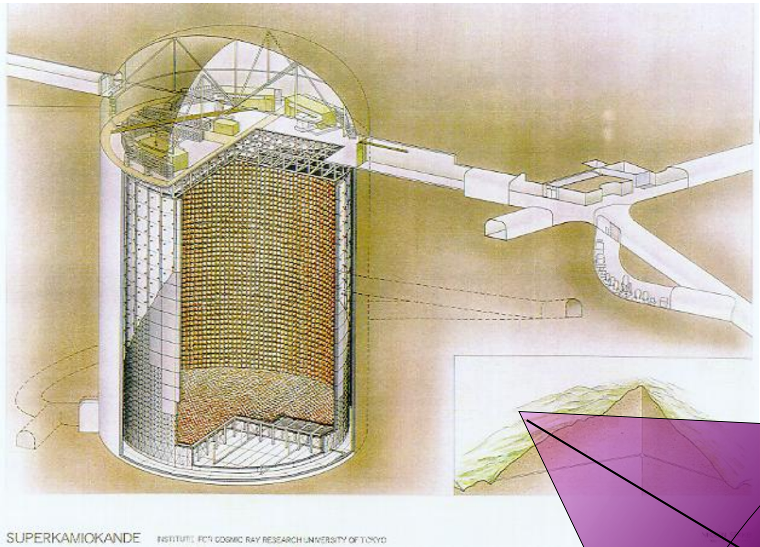
# Neutrino fluxes: what do we know/expect ?



# Detecting neutrinos in $H_2O$

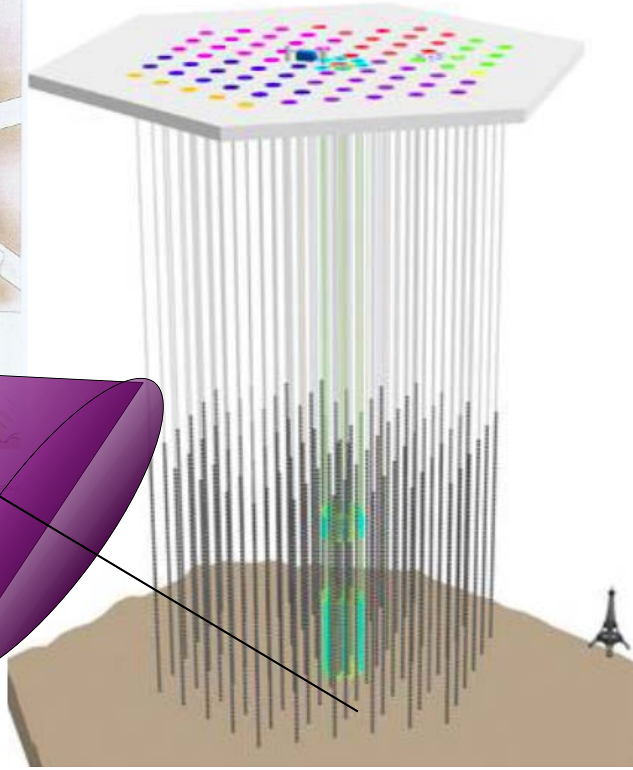
*Proposed by Greisen, Reines, Markov in 1960*

- DUMAND
- IMB
- Kamiokande
- Baikal
- AMANDA

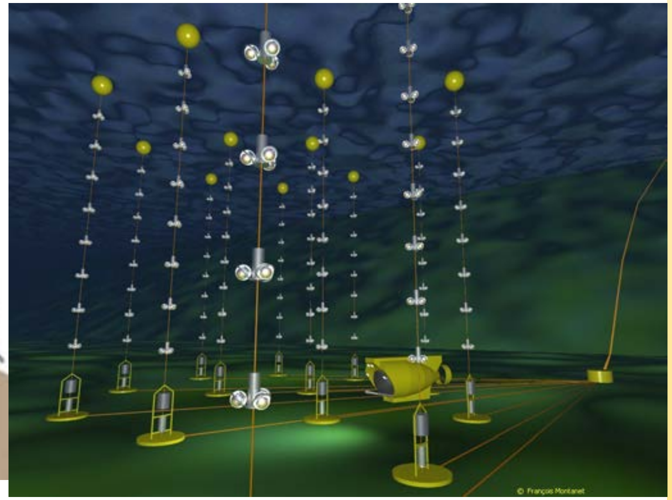



Super-K

SNO



**IceCube**



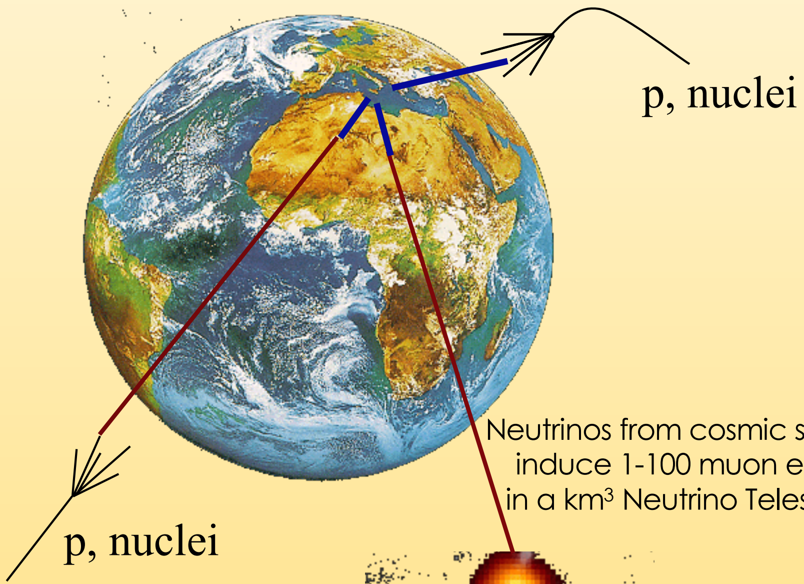
ANTARES

**Neutrino must interact to be detected**

# Schematics of a Cherenkov Neutrino Telescope

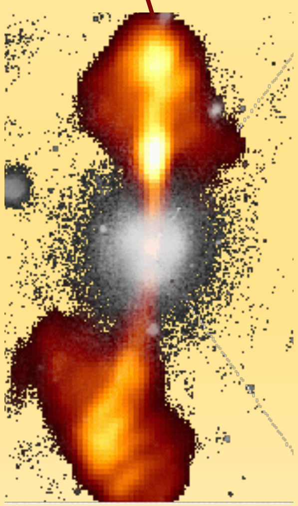
Search for neutrino induced events, mainly $\nu_\mu N \rightarrow \mu X$ , deep underwater

Down-going μ from atm. showers
S/N ~ $10^{-6}$ at 3500m w.e. depth




Neutrinos from cosmic sources induce 1-100 muon evts/y in a km³ Neutrino Telescope

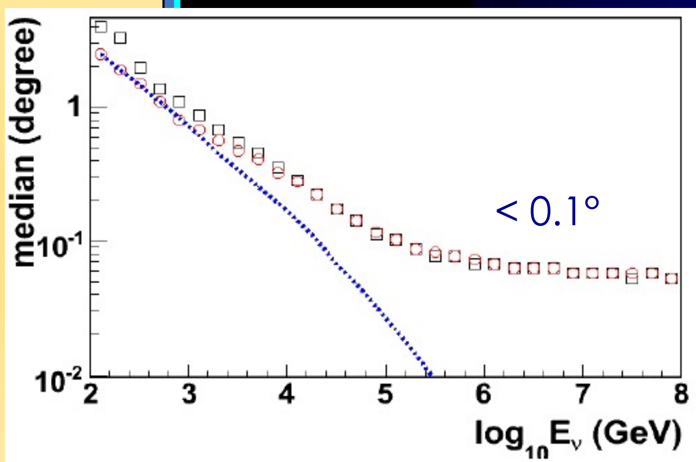
Up-going μ from neutrinos generated in atm. showers
S/N ~ $10^{-4}$

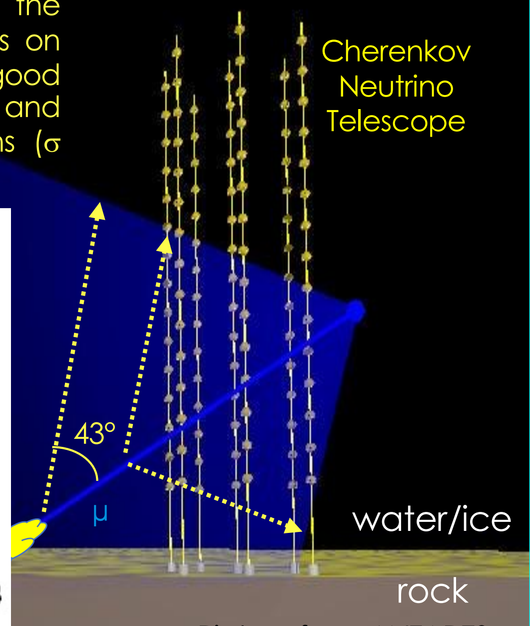


- Atmospheric neutrino flux ~ $E_\nu^{-3}$
- Neutrino flux from cosmic sources ~ $E_\nu^{-2}$
  - Search for neutrinos with $E_\nu$>1÷10 TeV
- ~TeV muons propagate in water for several km before being stopped
  - go deep to reduce down-going atmospheric μ backg.
  - long μ tracks allow good angular reconstruction

$$For\ E_\nu \geq 1 TeV \quad \theta_{\mu\nu} \sim \frac{0.7^\circ}{\sqrt{E_\nu[TeV]}}$$

μ direction reconstructed from the arrival time of Cherenkov photons on the Optical Modules: needed good measurement of PMT hits, σ(t)~1ns, and good knowledge of PMT positions (σ ~10cm)




Picture from ANTARES

# Neutrino Telescope physic's goal

## - search for ν from point like–sources:

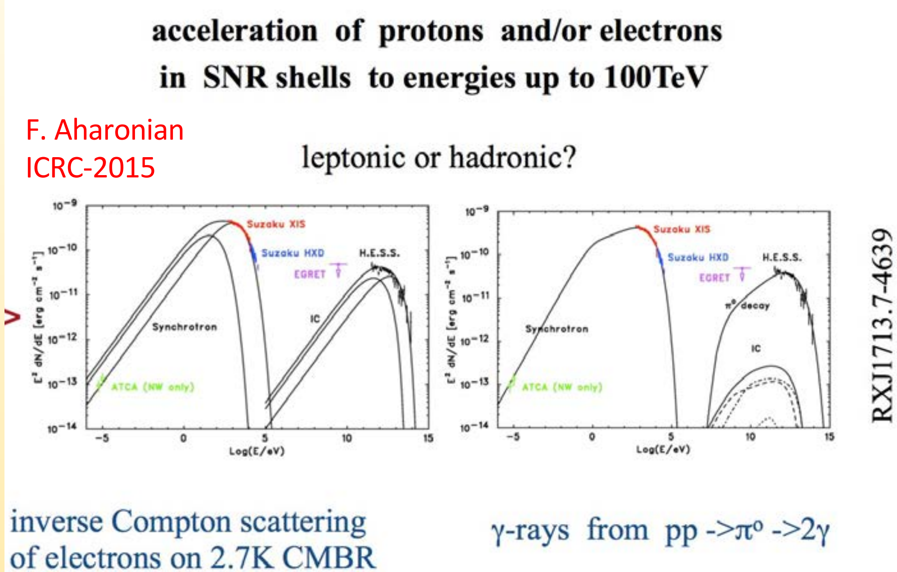
- **hadronic**

$$p_{CR} + p_{ISM} \rightarrow \pi^0\pi^\pm \ldots$$
$$\pi^0 \rightarrow \gamma\gamma(EM\ cascade)$$
$$\pi^\pm \rightarrow \nu_\mu, \nu_e \ldots$$

- **or leptonic ? (no ν expected)**

$$e_{H.E.} + \gamma_{sync} \rightarrow \gamma_{H.E.}$$

- **search for time-space coincidence with known sources: blazars, flaring (gamma, radio, ..) sources, GRBs, …**




## - search for "diffuse neutrino fluxes". is their origin related to:

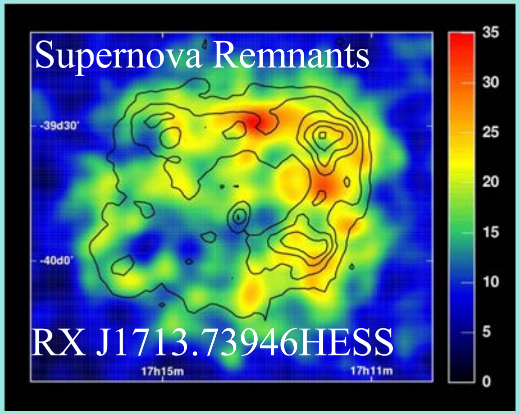
- **H.E. C.R. propagation ? What is the effect of the Galactic Ridge on their production?**
- **diffuse galactic γ background ?**

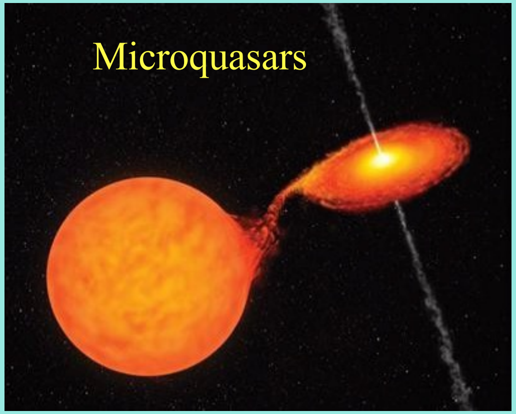
## - search for a p-γ-ν connection

- **H.E. ν (IceCube, ANTARES) - diffuse γ fluxes (FERMI)**
- **H.E. ν (IceCube, ANTARES) - U.H.E. C.R. (AUGER and T.A.)**

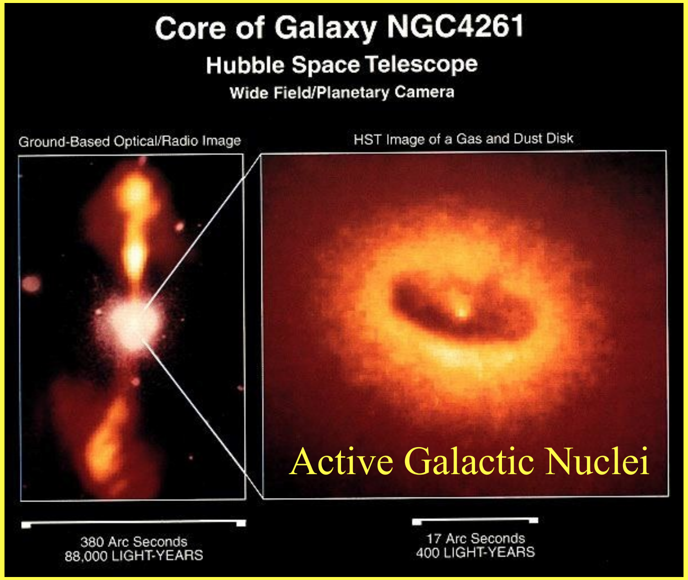
# Search for "Point like" cosmic Neutrino Sources

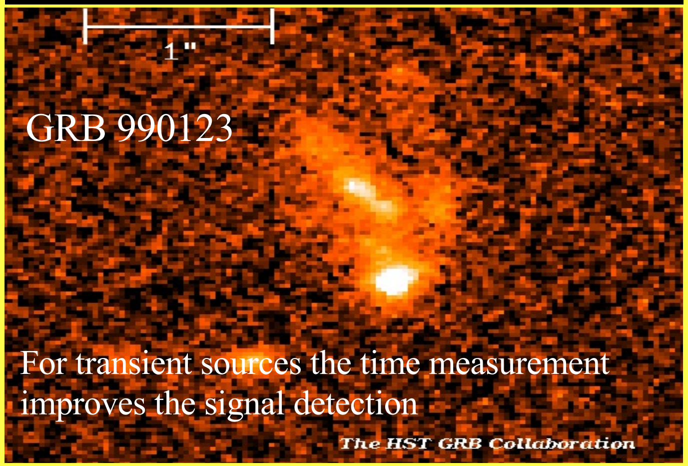
*Galactic*


*Extragalactic*




- Their identification requires a detector with accurate angular reconstruction

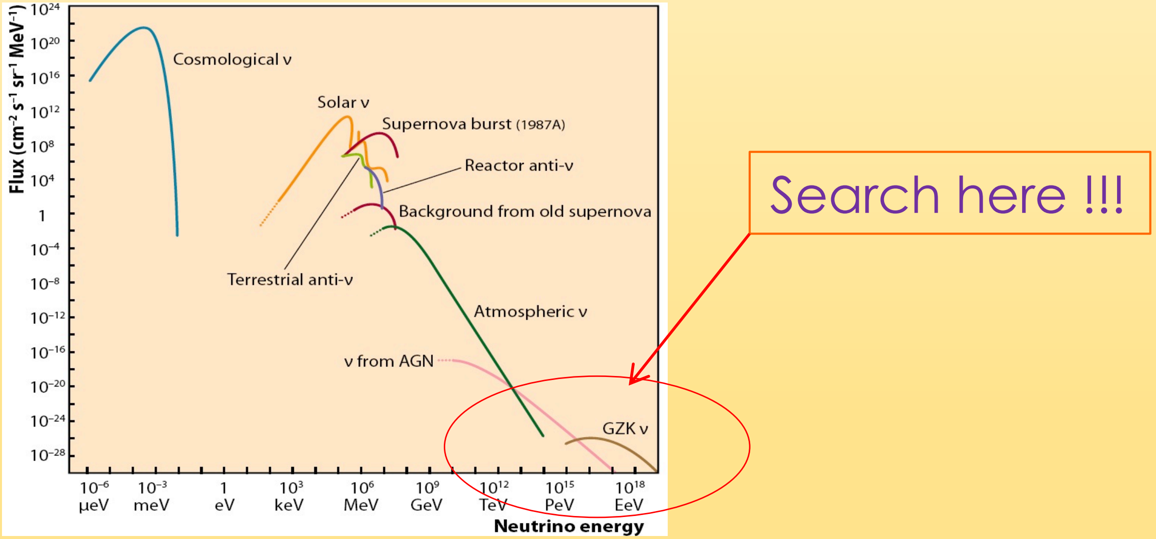
$$\sigma(\vartheta) \leq 0.5^\circ \text{ for } E_\nu \geq 1 TeV$$

**Experimental signal : statistical evidence of an excess of events coming from the same direction**

# Search for ν from "Diffuse Cosmic Neutrino Sources"

- **Unresolved AGN**
- **Neutrinos from "Z-bursts"**
- **Neutrinos from "GZK like" p-CMB interactions**
- **Neutrinos foreseen by Top-Down models**
- **….**

**Their identification out of the more intense background of atmospheric neutrinos (and muons) is possible at high energies (E > TeV) and implies accurate energy reconstruction.**

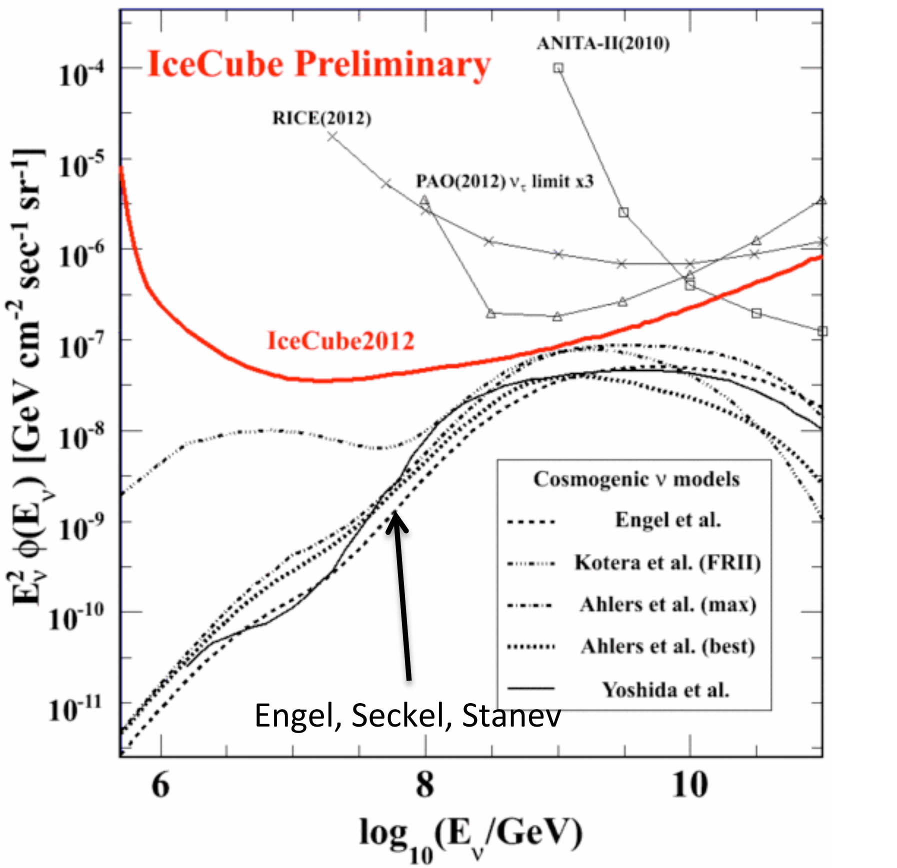



- **2013, first evidence for a diffuse flux of cosmic neutrinos: 28 contained VHE astrophysical ν events reported by IceCube**

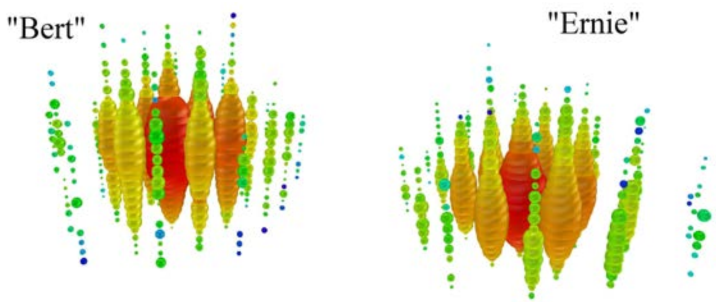
# … looking for the discovery of neutrino point like sources … search for cosmic neutrinos (also known as GZK $\nu$ )

$$p + \gamma_{\mathrm{CMB}} \rightarrow n + \pi^{+} \rightarrow n\ \mu^{+}\ \nu_{\mu}$$

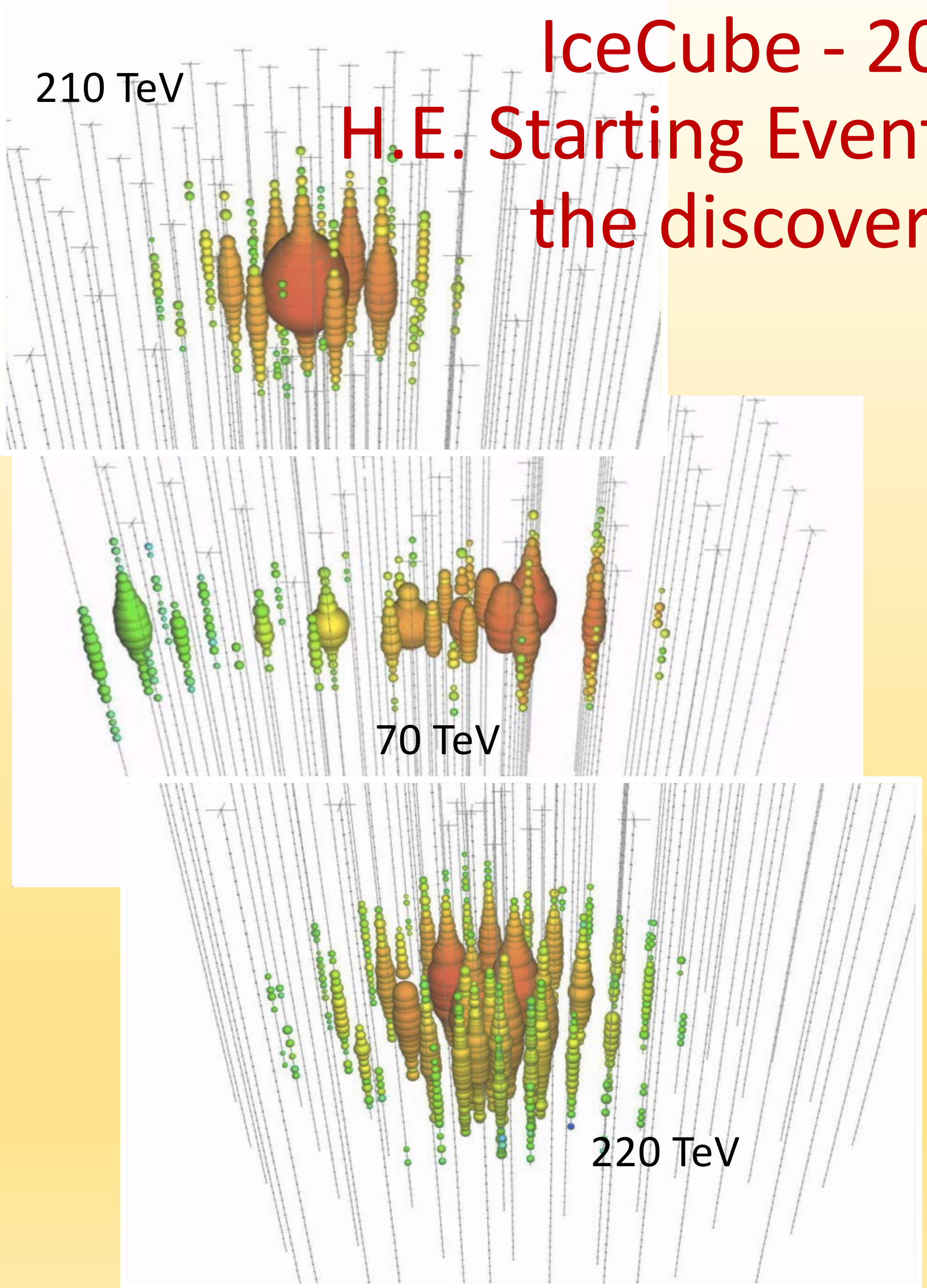
Limits from IC-79 + IC-86, May 2010-May2012

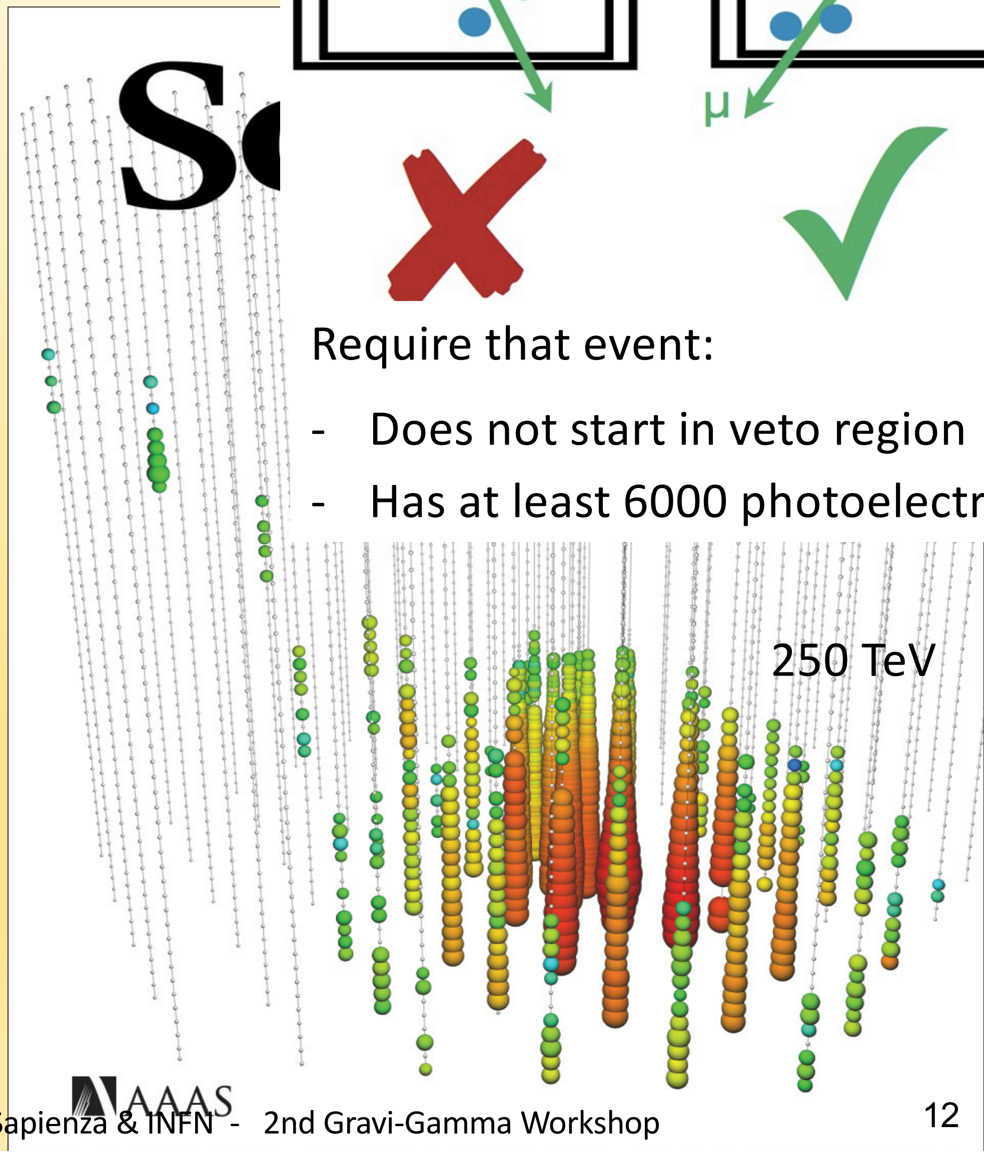


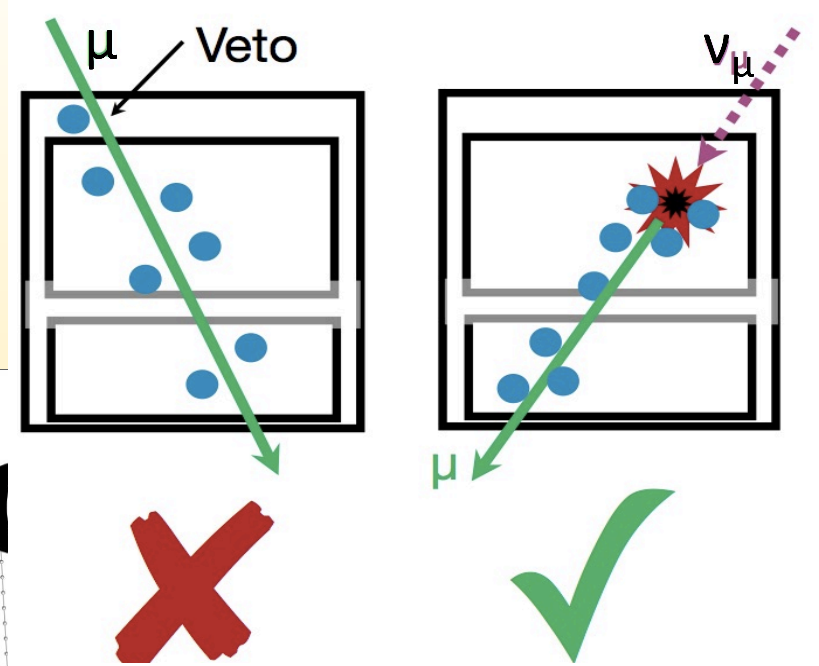

This search discovered two PeV cascade events, each with just over 1 PeV deposited energy--lower than expected for cosmogenic neutrinos. The events were just at the threshold of the search.



# IceCube - 2013
# H.E. Starting Event Analysis
# the discovery !!




Require that event:

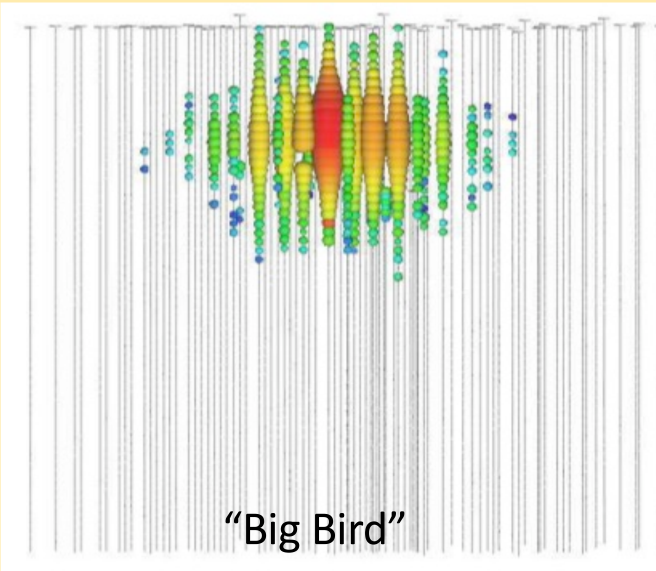
- Does not start in veto region
- Has at least 6000 photoelectrons

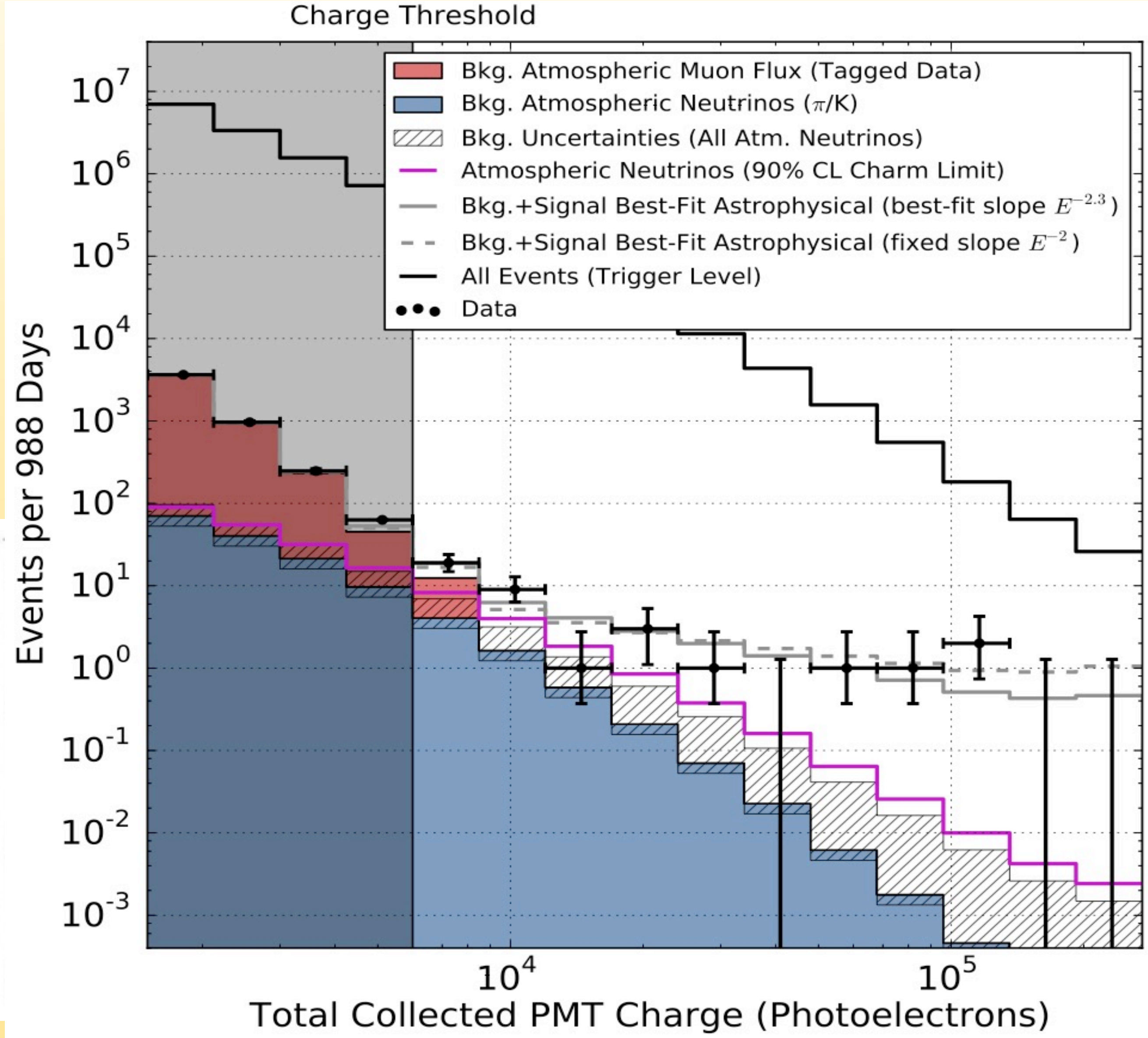
# High Energy Starting Event Analysis

**3-Year Analysis**
PRL **113**, 101101 (2014)

36 events in 3 years

Three > PeV events seen in three years, including a 2-PeV neutrino



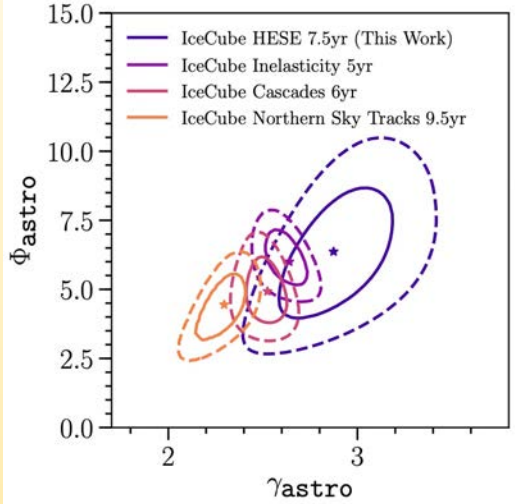
# IceCube 7.5 years data sample - HESE Analysis

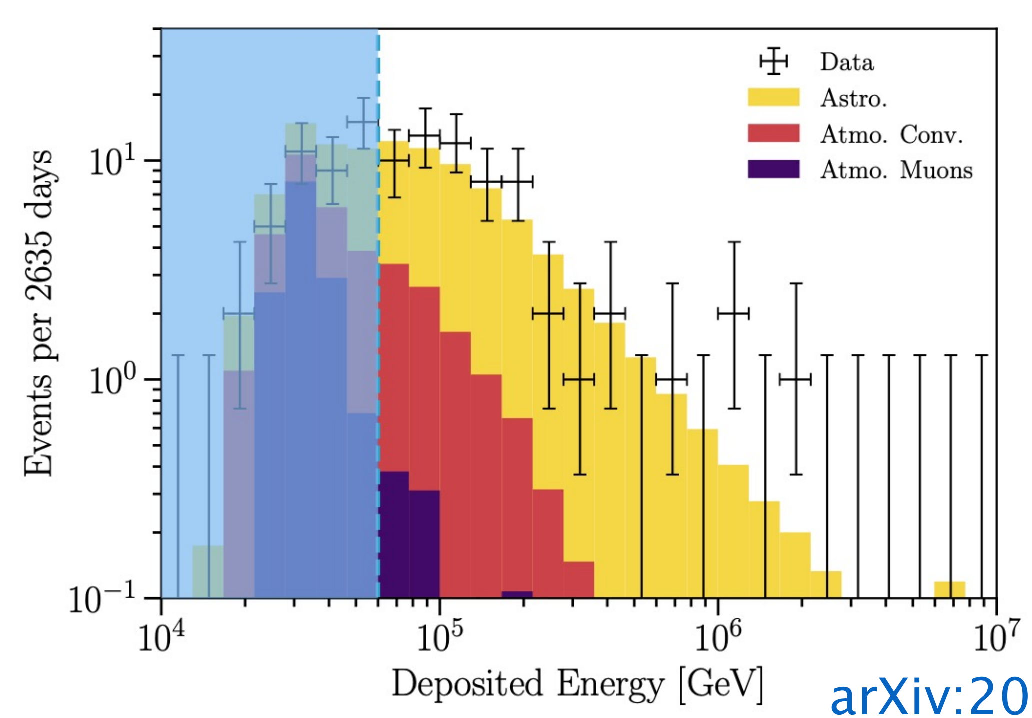
- The measured sample is compatible with a total flux of $\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$ spectrum

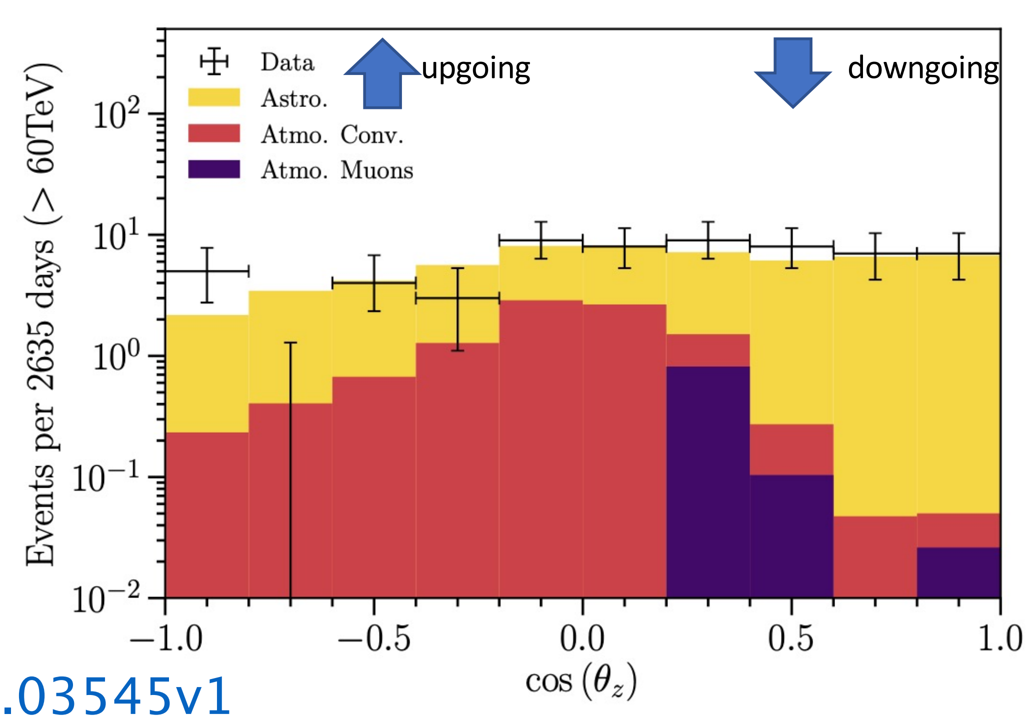
$$\frac{d\phi}{dE} = 2.3^{+0.3}_{-0.3}\left(\frac{E_\nu}{100TeV}\right)^{-2,87^{+0.20}_{-0.19}} \cdot 10^{-18} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

- The hypothesis that HESE are due to "prompt atmospheric neutrinos" is rejected at > 5σ with respect to a single power-law astrophysical plus atmospheric flux hypothesis

| Category | $E < 60$ TeV | $E > 60$ TeV | Total |
|---|---|---|---|
| Total Events | 42 | 60 | 102 |
| Up | 19 | 21 | 40 |
| Down | 23 | 39 | 62 |
| Cascade | 30 | 41 | 71 |
| Track | 10 | 17 | 27 |
| Double Cascade | 2 | 2 | 4 |



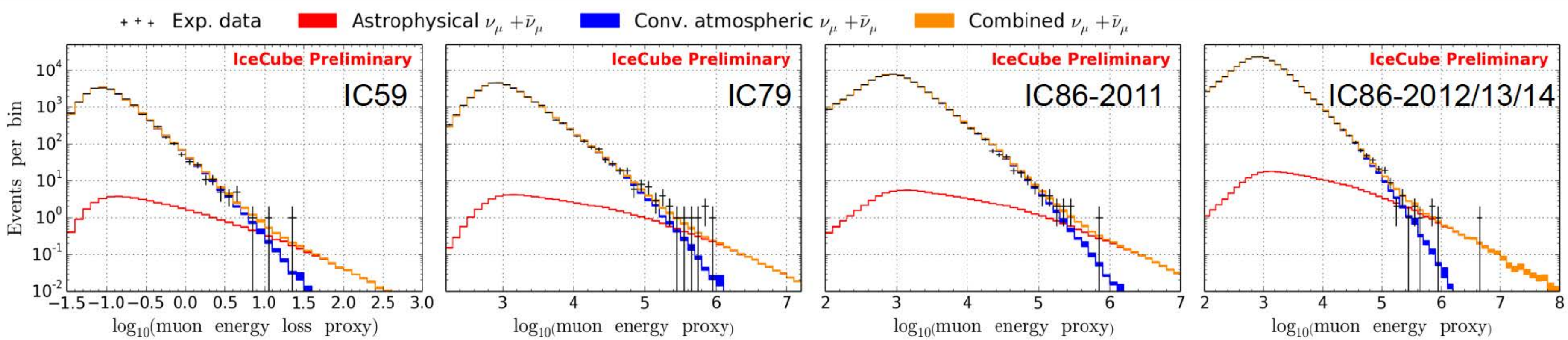



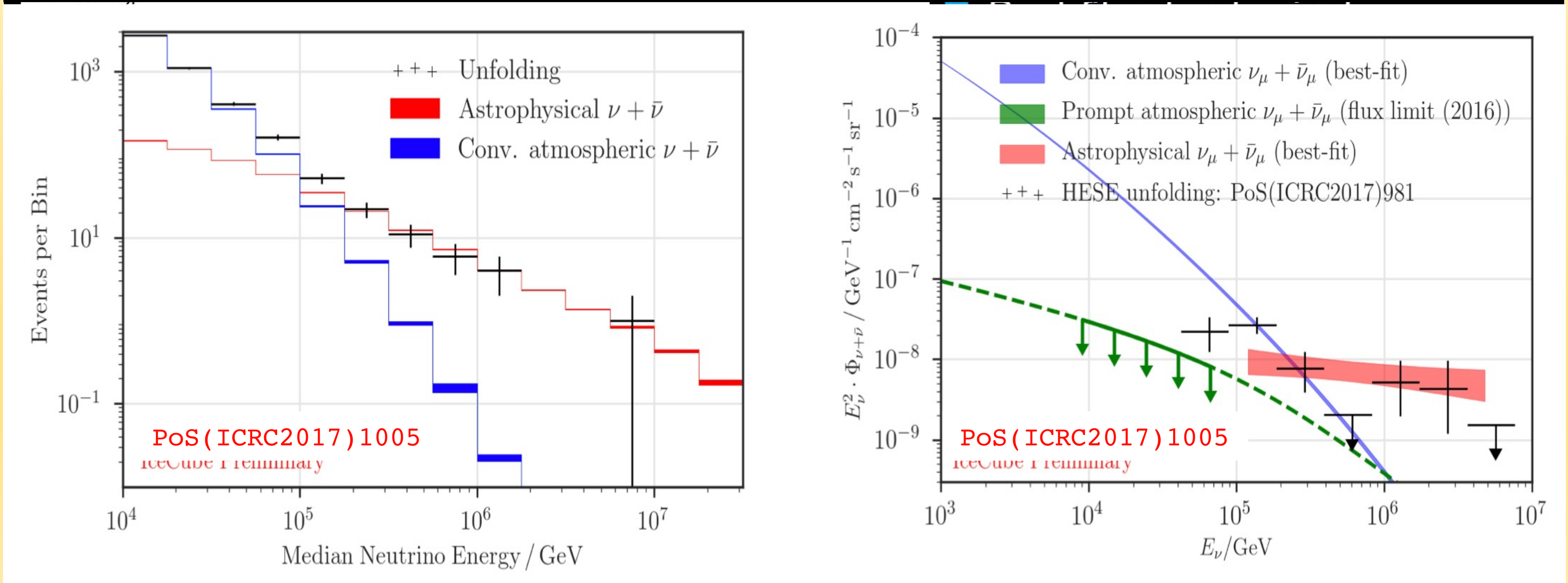

arXiv:2011.03545v1

# IceCube today: diffuse $\nu_\mu$ flux with up-going muons

## after 7 years → 6.4 sigma

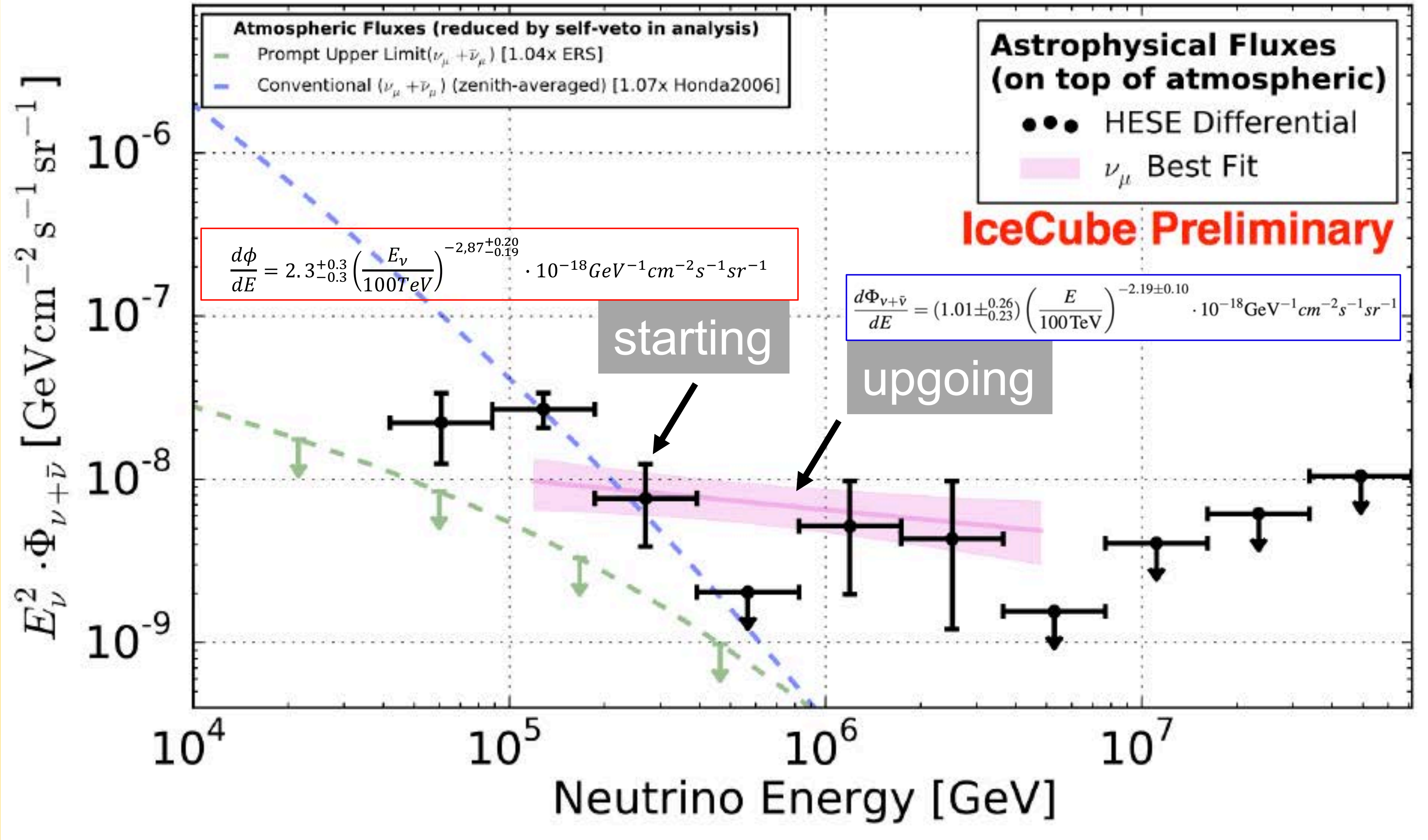



## At ICRC 2017, 8 years data sample → 6.7 sigma



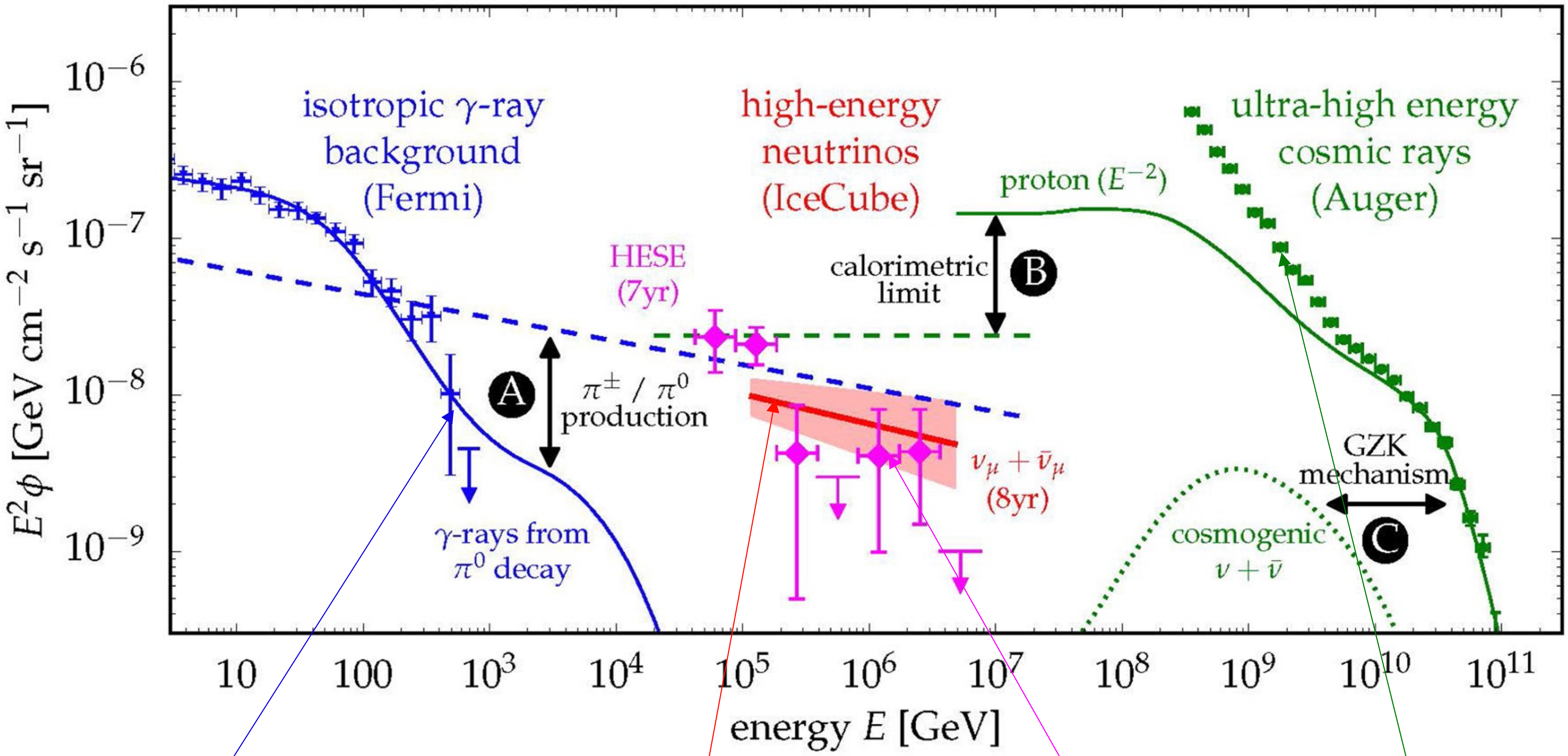
# IceCube 2017

High Energy Staring Events and up-going muons analyses give ~ consistent results (?)



# The p - γ - ν connection

Halzen and Kheirandish, 2019 doi: 10.3389/fspas.2019.00032




isotropic diffuse gamma ray spectrum

ultra-high-energy cosmic rays

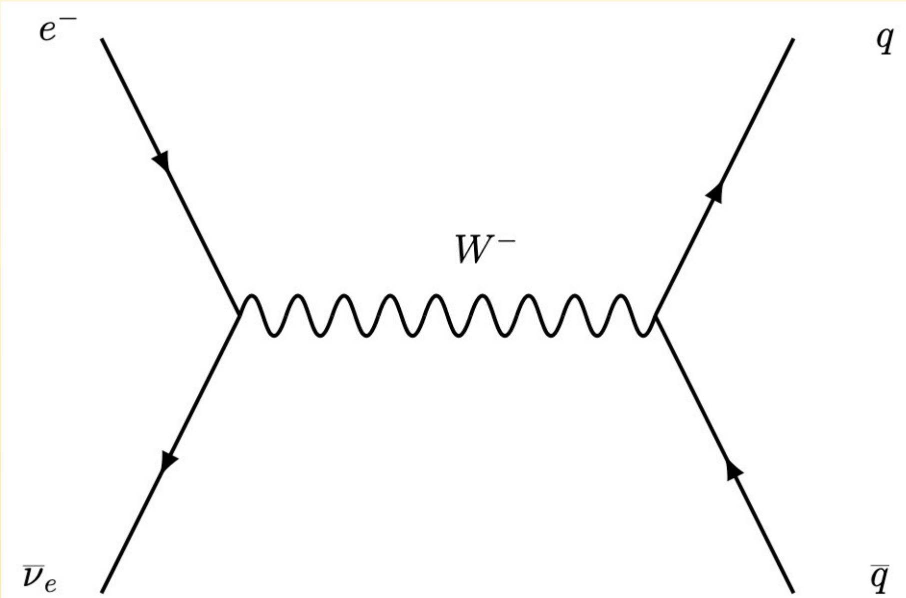
spectral ν flux from the 7-years HESE analysis

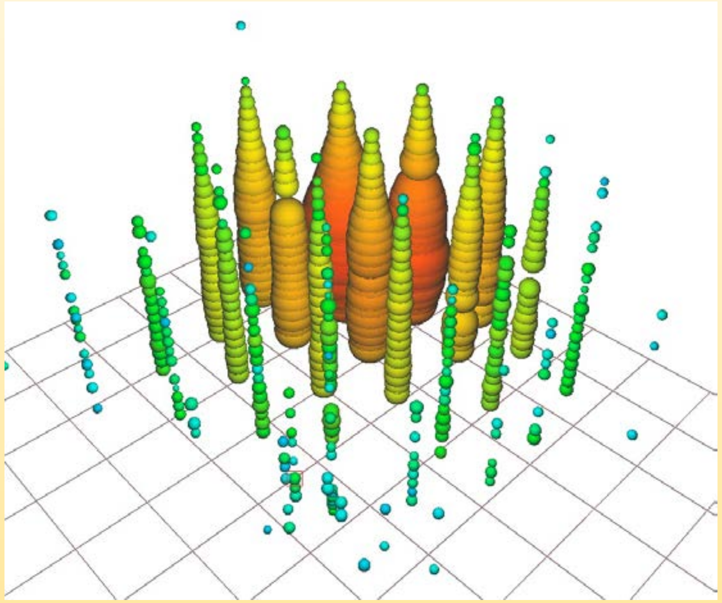
spectral flux (ϕ) of $\nu_\mu$ from the 8-years upgoing track analysis

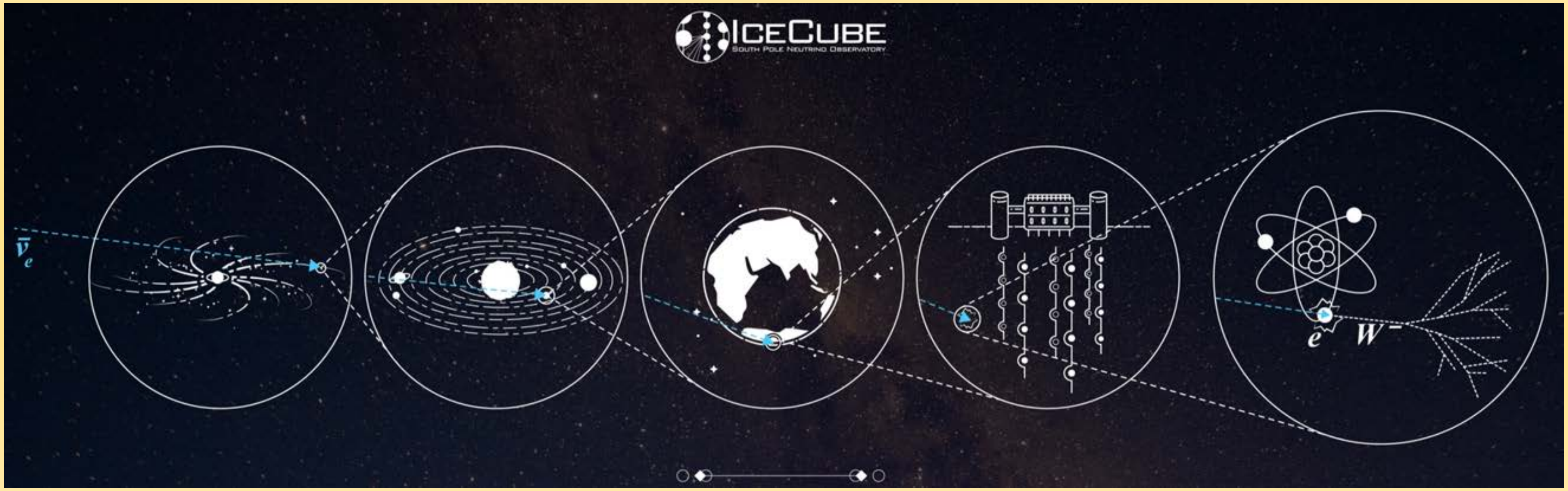
# IceCube and the Glashow resonance

On December 8, 2016, IceCube: first observation of

$$\bar{\nu}_e \, e \rightarrow W^- \quad (E_{\bar{\nu}_e} \sim 6.3 \; PeV)$$



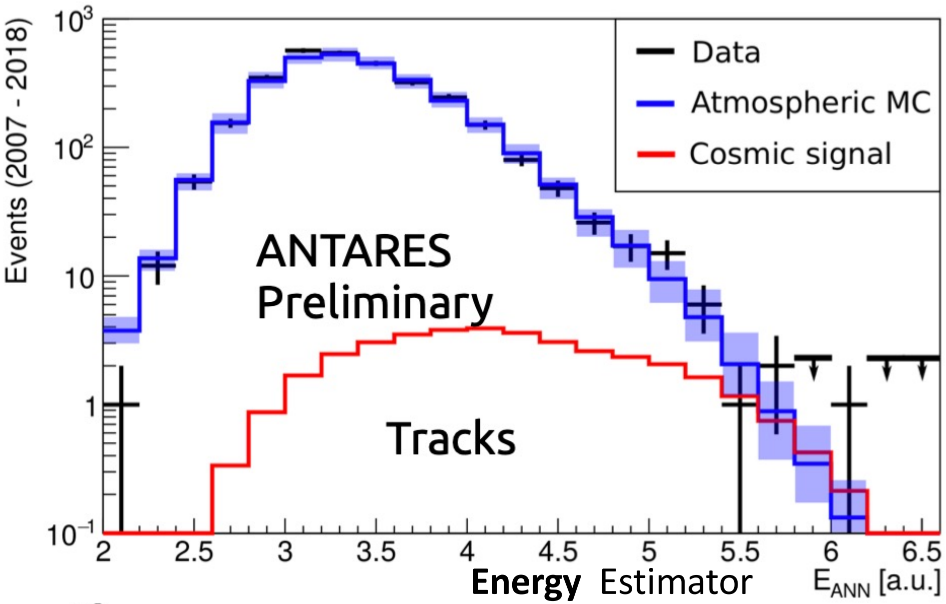



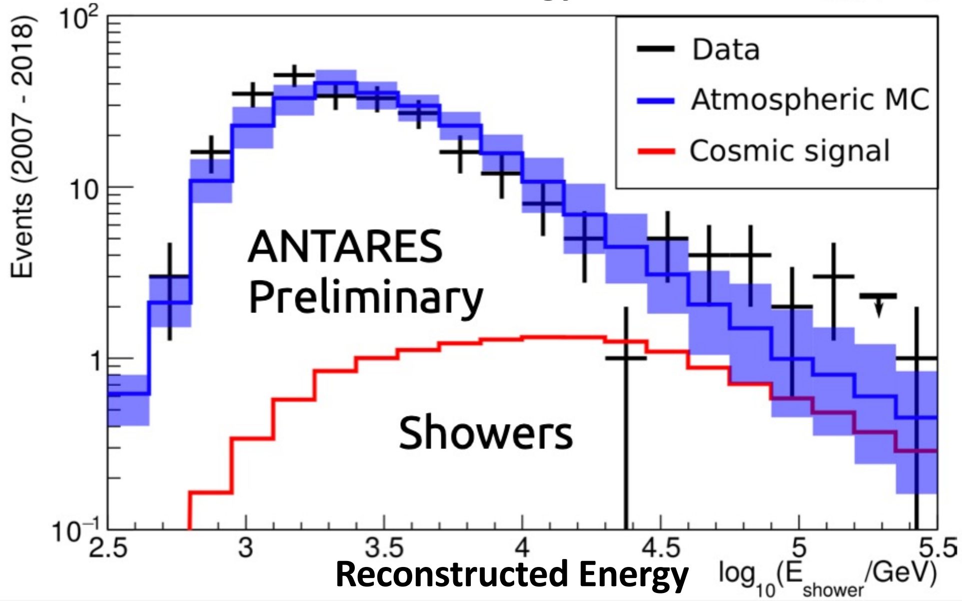


# ANTARES recent results on the search for diffuse ν flux

## The ICRC19 results, 2016-2018 added-up

**PoS (ICRC2019) 891**



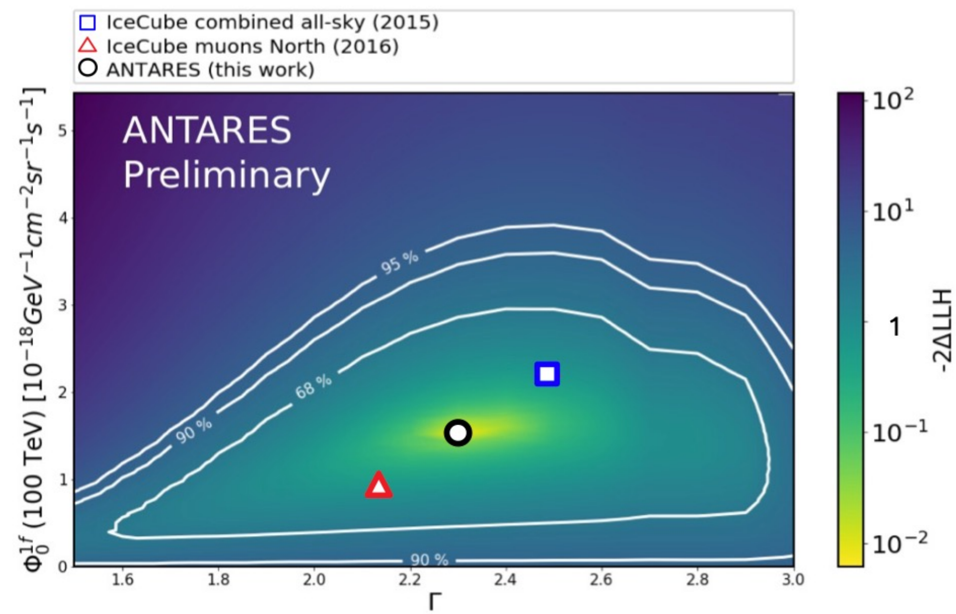




**~same event selection**

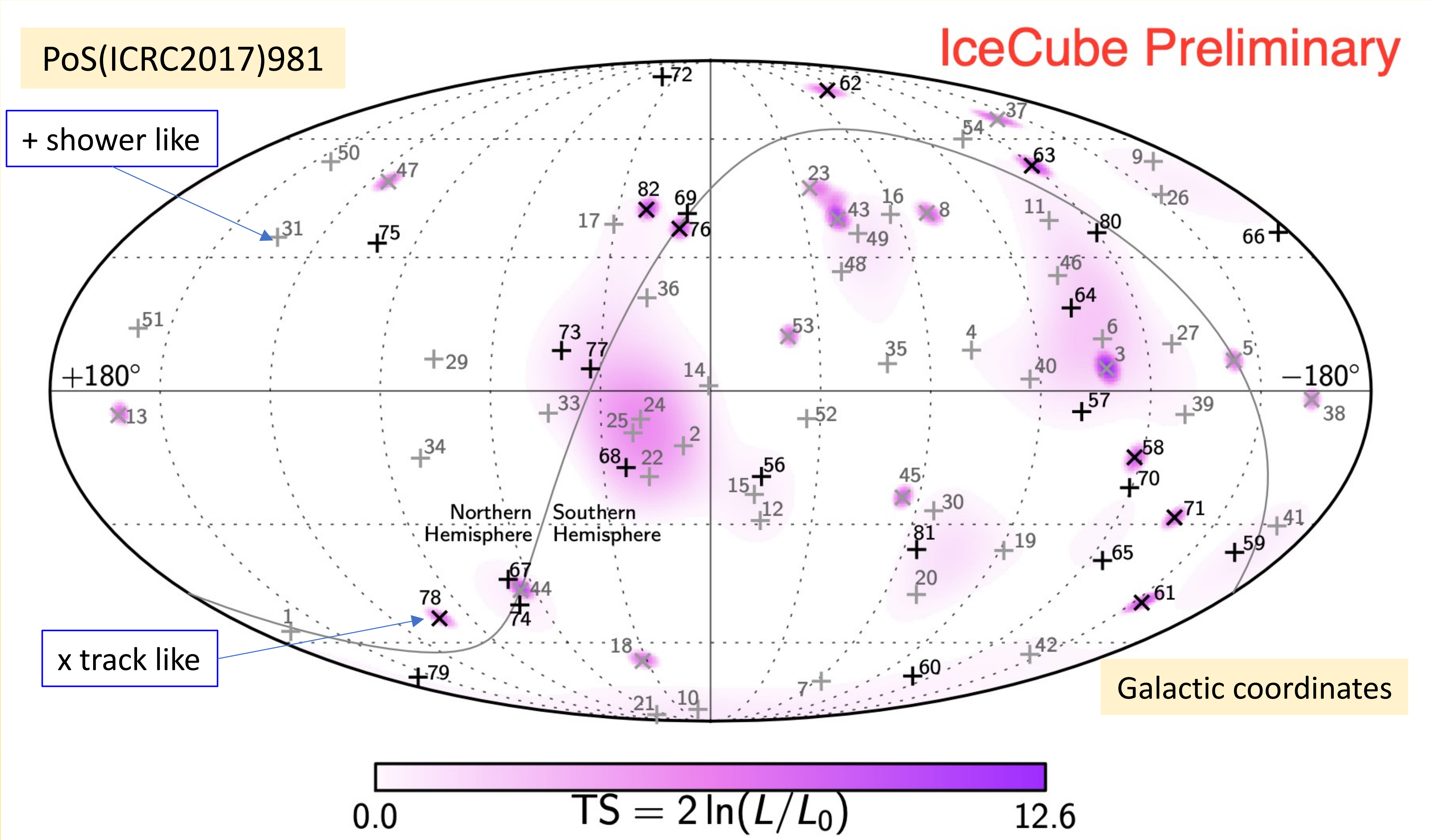
**Overall → data: 50** events
(**27** tracks + **23** showers)

**Overall → bkg MC: 36.1 ± 8.7** (stat.+syst.)
(**19.9** tracks and **16.2** showers)

**1.8σ excess**
**0-cosmic excluded c.l. >90%**



# Where these neutrinos are coming from ??



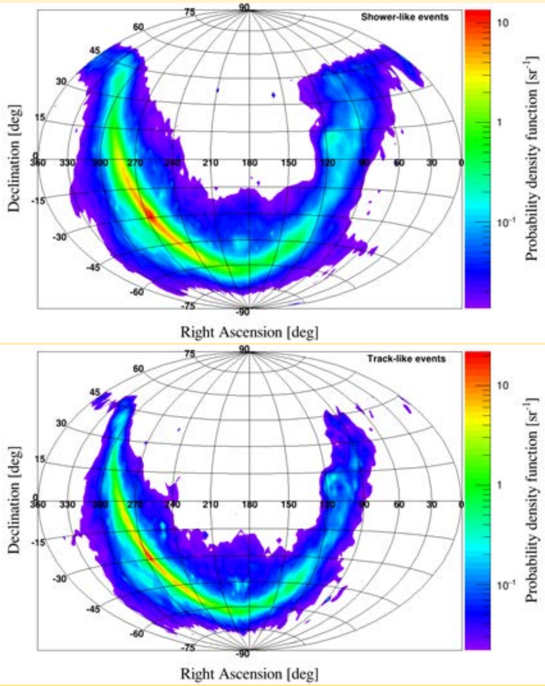

No significant clustering observed

A diffuse flux from extragalactic sources. A subdominant Galactic component cannot be excluded.

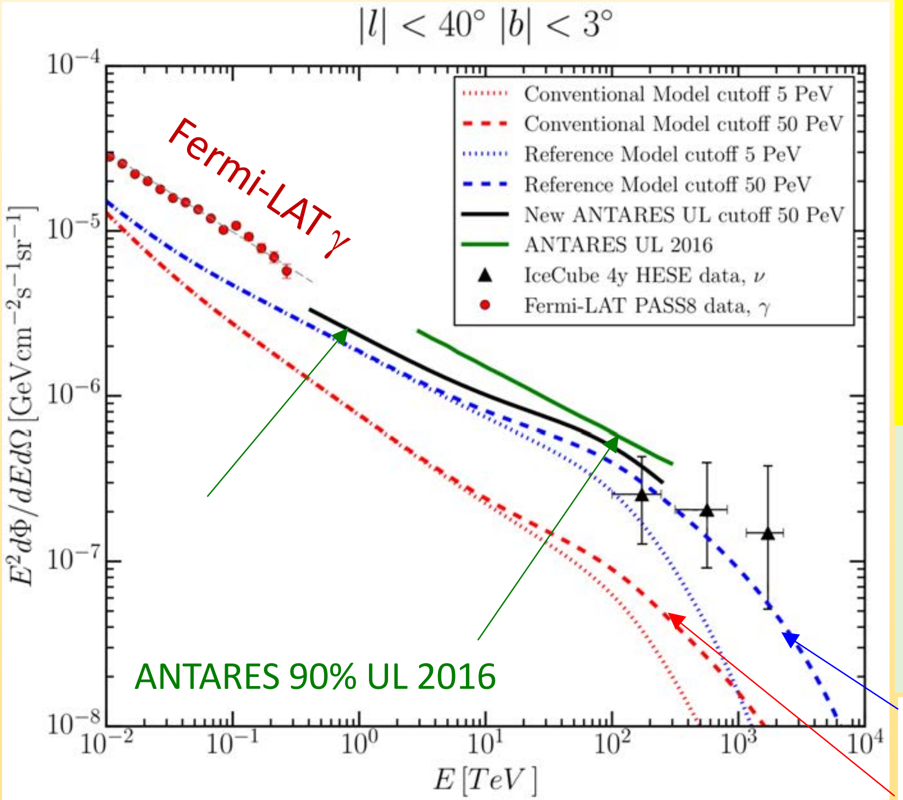
# Search for neutrinos from the Galactic plane

New analysis on tracks and showers, based on Max. Lik.

$$\mathcal{L}_{sig+bkg} = \prod_{\tau\in\{tr,sh\}} \prod_{i\in\tau} [\mu_{sig}^{\tau} \cdot pdf_{sig}^{\tau}(E_i, \alpha_i, \delta_i) + \mu_{bkg}^{\tau} \cdot pdf_{bkg}^{\tau}(E_i, \alpha_i, \delta_i)]$$




ANTARES arXiv:1705.00497v1
1 May 2017




KRA$_\gamma$ new model to describe the C.R. transport in our galaxy. It agrees with C.R. measurements (KASCADE, Pamela, AMS, Fermi-LAT, HESS).
FERMI-LAT diffuse γ flux from along the galactic plane ($\pi^0 \rightarrow \gamma\gamma$) well explained above few GeV.

KRA$_\gamma$ allows to predict the ν flux by $\pi^{\pm}$ decays induced by galactic CR interactions

KRA$_\gamma$ 50PeV cut-off for CR
KRA$_\gamma$ 5PeV cut-off for CR

**KRA$_\gamma$ assuming a neutrino flux ∝ E$^{-2.5}$ and a CR spectrum with 50 PeV cut-off can explain ~20% of the IceCube observed HESE.**

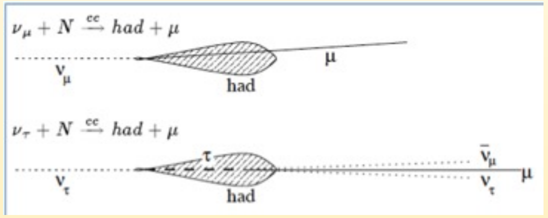
ANTARES, with an good visibility of the Galactic Plane well suited to observe these fluxes or to put competitive limits: no signal found → set 90%C.L. upper limits.

# It's mandatory now !!!!

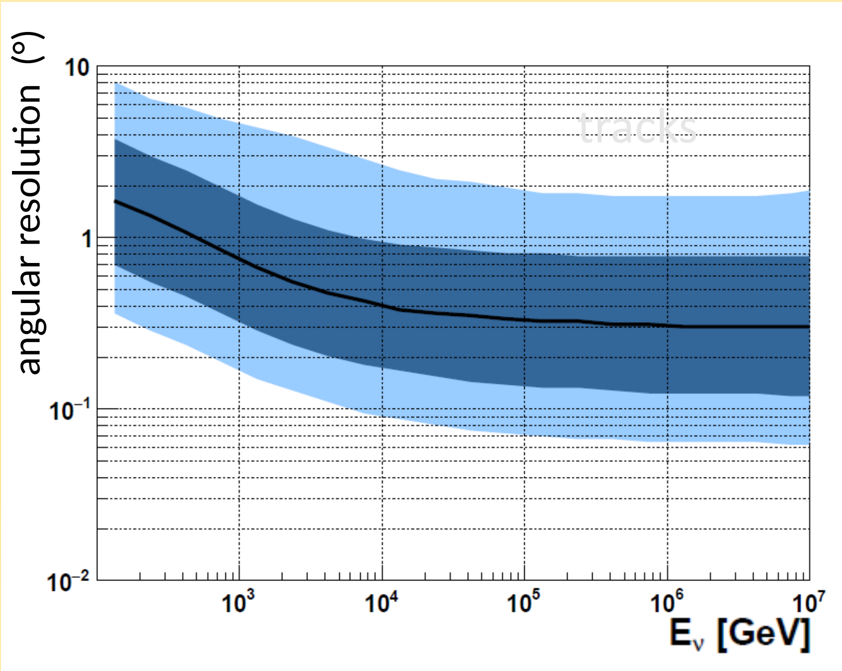
- **Let search for neutrino point like sources:**
  - Large size detector required (very small fluxes expected)
  - Very good accuracy in angular reconstruction (high background, the irreducible atmospheric background has to be subtracted statistically)

# The ANTARES search for point-like ν sources based on two kind of events

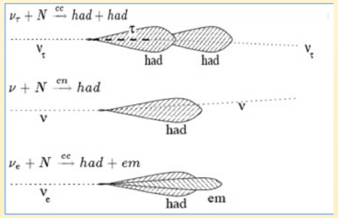
- Tracks: CC $\boldsymbol{\nu_\mu}$ or $\boldsymbol{\nu_\tau} \rightarrow \boldsymbol{\mu}$



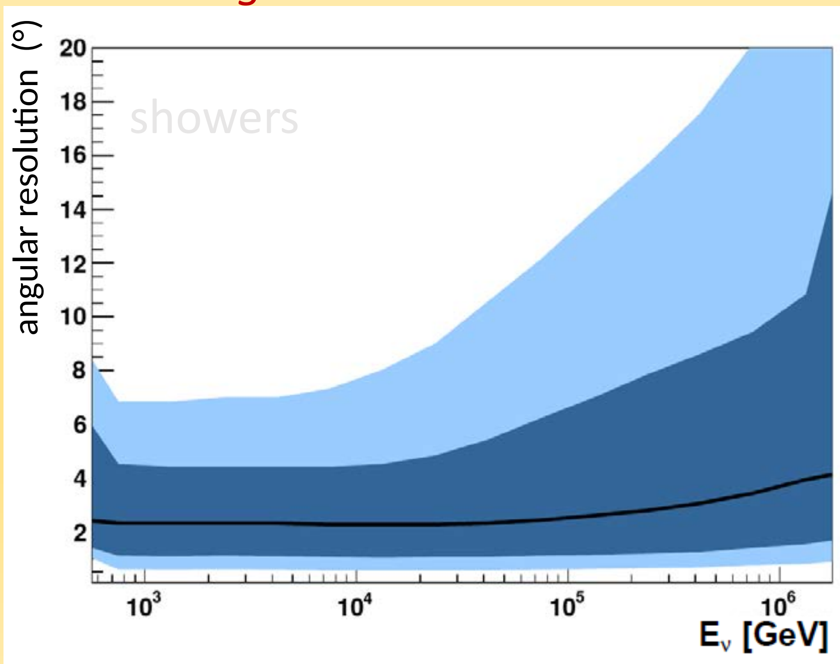

- Interaction can occur far from the detector providing a large *Effective Volume*
- *Angular resol.* $< \mathbf{0.4}°$ for $\boldsymbol{E_\nu} > \mathbf{10}\ \boldsymbol{TeV}$
- *Energy resol.* ~ factor 3




- Electronic or hadronic showers: NC and CC $\boldsymbol{\nu_e}$ or $\boldsymbol{\nu_\tau} \rightarrow$ showers




- Events contained in the detector: smaller *Effective Volume,*
- *Energy resolution ~ 5-10%*
- *Median angular resolution* $\sim \mathbf{3}°$

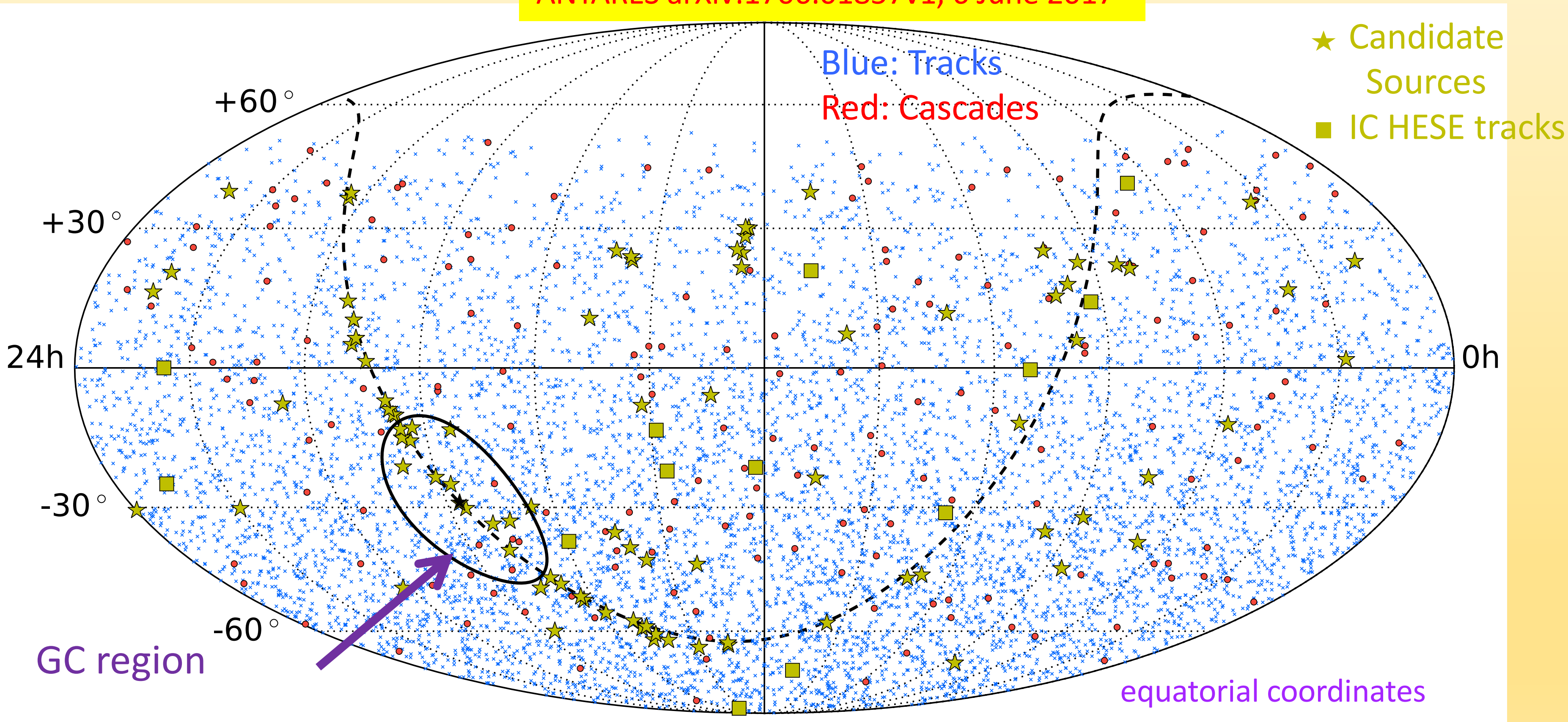


# **ANTARES** Search for cosmic ν from known point-like Sources

9 years of ANTARES data searching for all neutrino flavours:
7629 “tracks” + 180 “shower” events passed the selection criteria

$$log\mathcal{L}_{sig+bkg} = \sum_{S=tr.,sh.} \sum_{\tau=S} log[\mu^{\tau}_{sig} \cdot \mathcal{F}^{\tau}_{sig}(\delta) \cdot \mathcal{P}^{\tau}_{sig,i}(E_i) + \mathcal{N}^{\tau} \cdot \mathcal{B}^{\tau}_{i} \cdot \mathcal{P}^{\tau}_{bkg,i}(E_i)] - \mu_{sig}$$

ANTARES arXiv:1706.01857v1, 6 June 2017

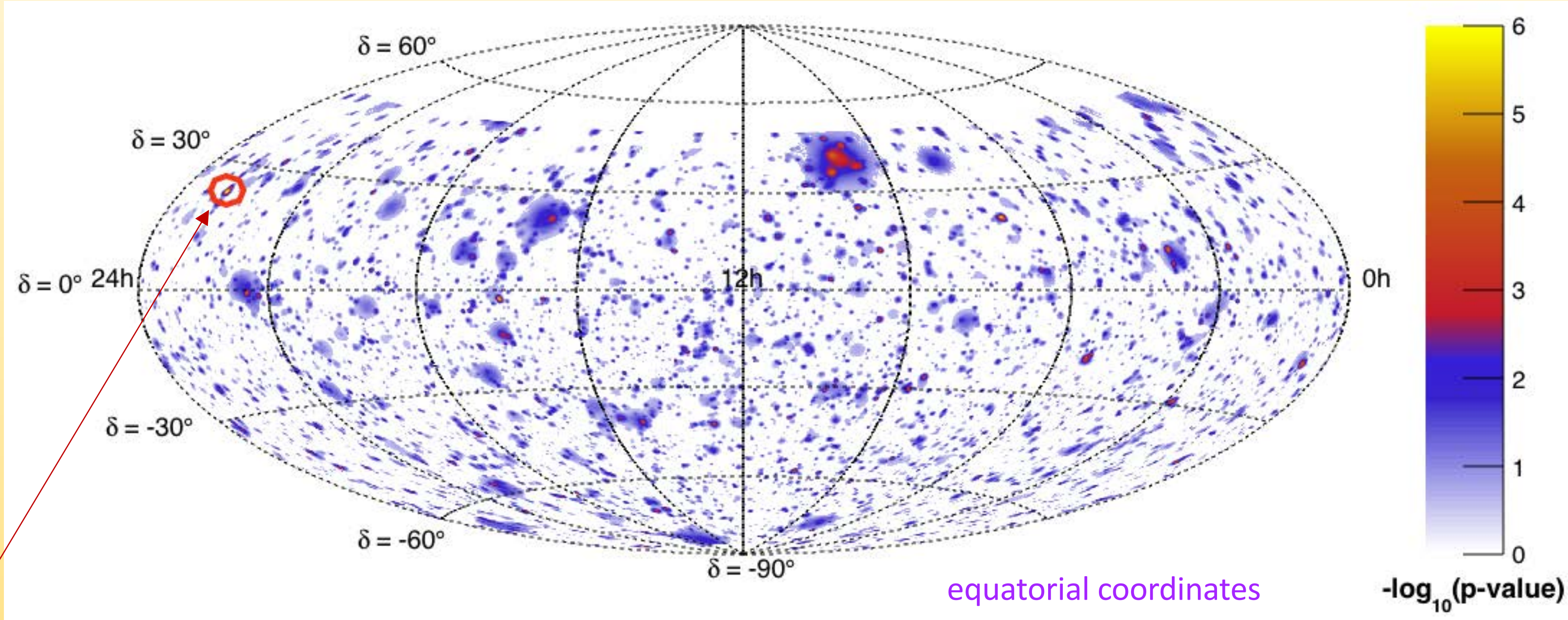



here …. no significant excess has been found … but keep tuned

# ANTARES results: “full sky search” of ν sources

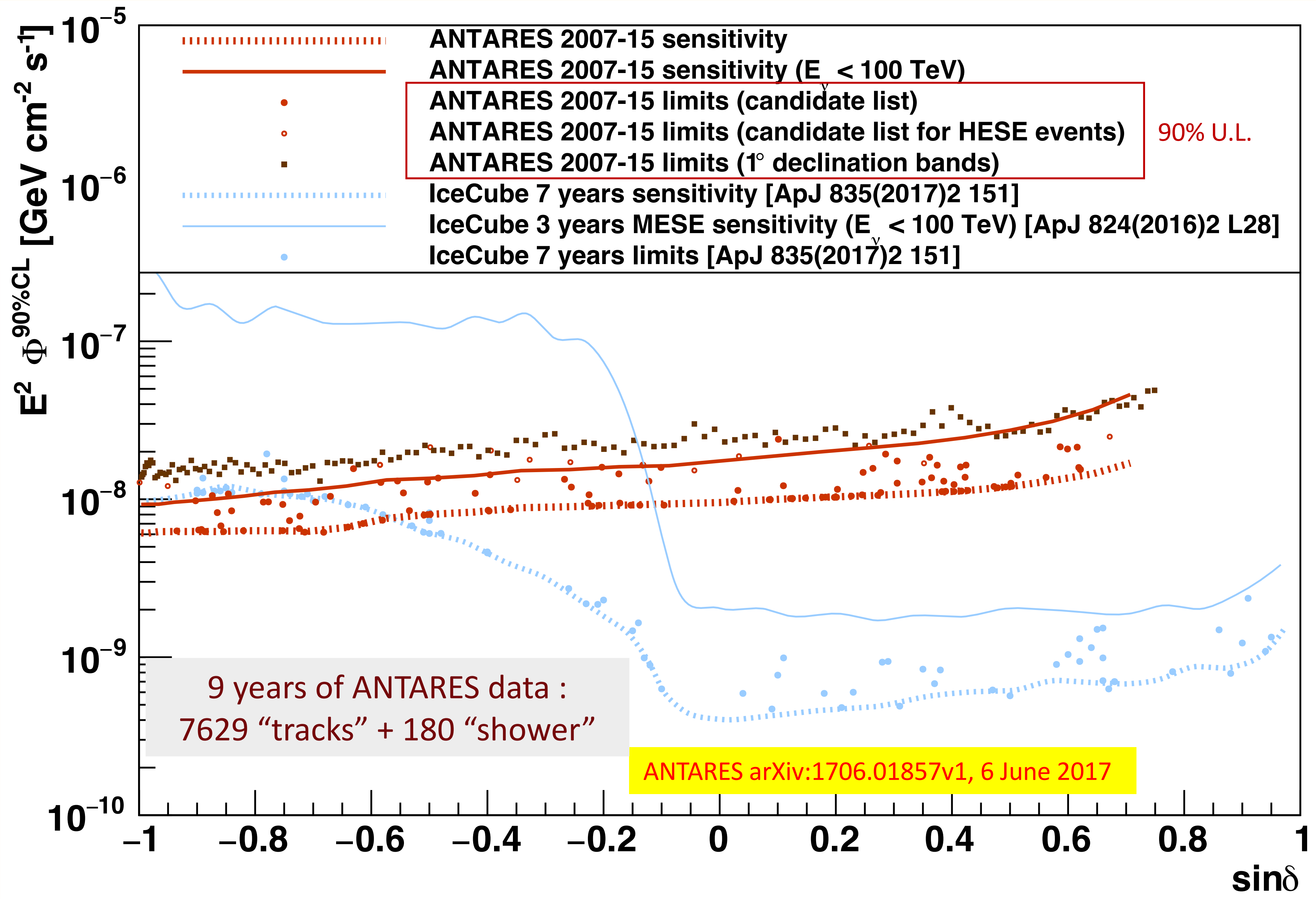
The visible sky of ANTARES divided on a $1^0 \times 1^0$ (r.a x decl.) boxes. Maximum Likelihood analysis searching for clusters

ANTARES arXiv:1706.01857v1, 6 June 2017



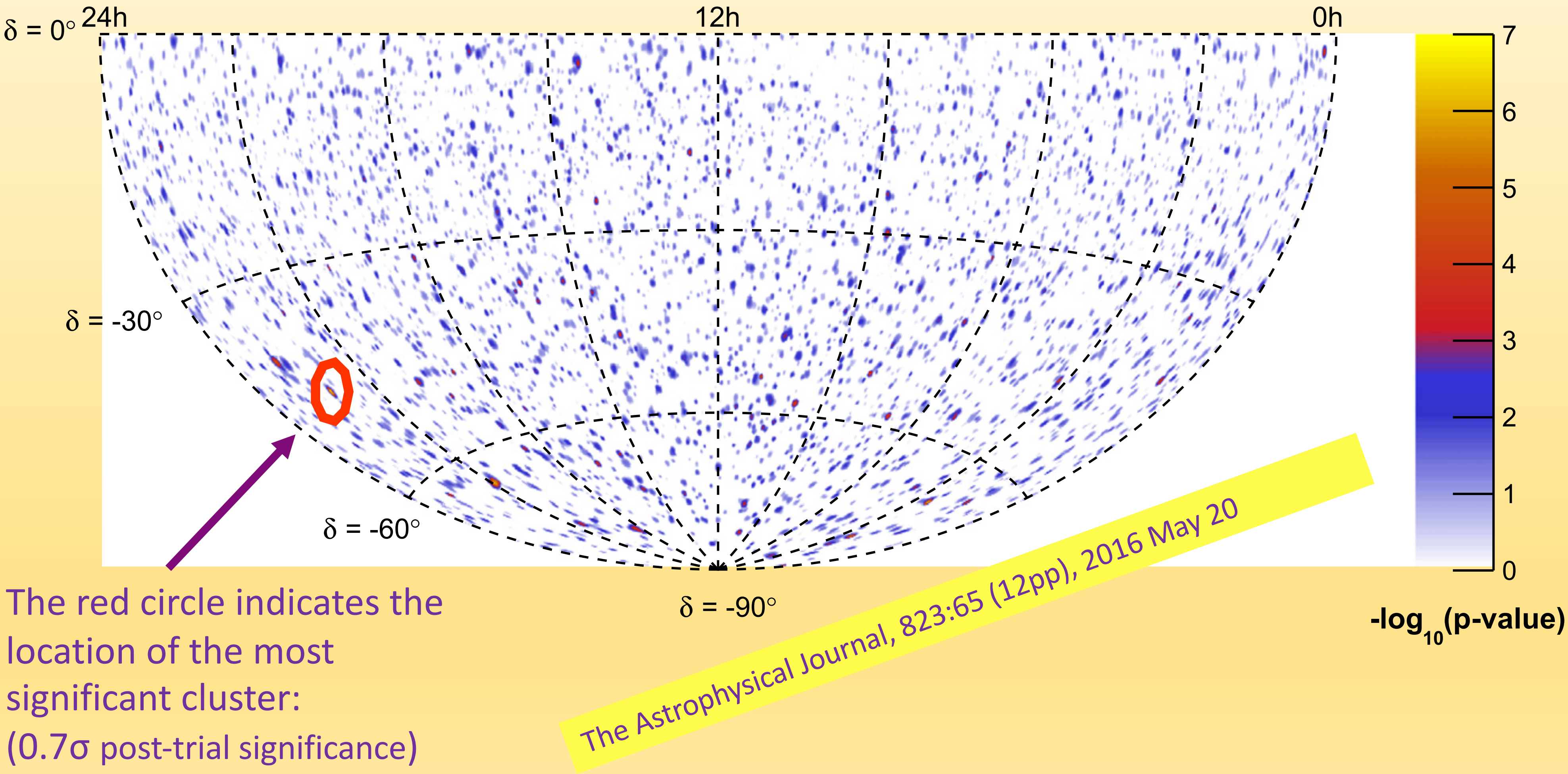

The most significant cluster: decl. $\delta = 23.5^0$, r.a. $\alpha = 343.8^0$ has a pre-trial p-value of $3.84\times10^{-6}$
→ U. L. from this sky location $E^2 \frac{d\Phi}{dE} = 3.8\times10^{-8}$ GeV cm$^{-2}$ s$^{-1}$

# ANTARES & IceCube: "full sky search" of ν sources



# Joint IceCube + ANTARES search for ν sources

Skymap of pre-trial p-values for the combined ANTARES 2007/12 and IceCube 40, 59, 79 point-source analyses.




The red circle indicates the location of the most significant cluster: (0.7σ post-trial significance)

# The Multi-Messenger Search Programme with a neutrino Telescope

The case for ANTARES

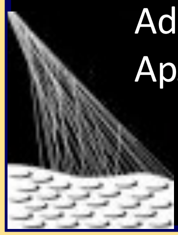
Neutrinos trigger others

Others trigger neutrinos


**ANTARES ⟺ VIRGO LIGO**

common working group (GWHEN)
S. Adrián-Martínez et al.,
JCAP 06 (2013) 008

**ANTARES ⟺ AUGER**



Adrian-Martinez et al.,
ApJ 774 (2013) 008

TAToO
(Telescopes – ANTARES Target of Opportunity)

Optical follow-up of neutrino alerts for transient source search (GRBs, SNae).
Analysis in progress!

**ANTARES ⟺ Optical Telescopes**
TAROT & ROSTE + more

Ageron *et al.*, *Astrop.Phys* 35 (2012) 530-536

Flaring Sources
($\nu$ emission from $\gamma$-flaring blazars/$\mu$Quasars)

**ANTARES ⟺ Gamma-Rays X-Rays**

**blazars: APP 36 (2012) 304;**
**$\mu$Quasars: JHEAp, 3-4 (2014) 9-7**

GCN (Gamma-ray Coordination Network)

**ANTARES ⟺ GCN**

**A&A 559, A9 (2013),**
**JCAP 1303 (2013) 006**

# A Multi-Messenger Search of ν from GRB

GCN alerts trigger the recording of all the low level triggers. A continuous buffer ensures the availability of the data before the alert

GCN=Gamma Ray Burst Coordination Network

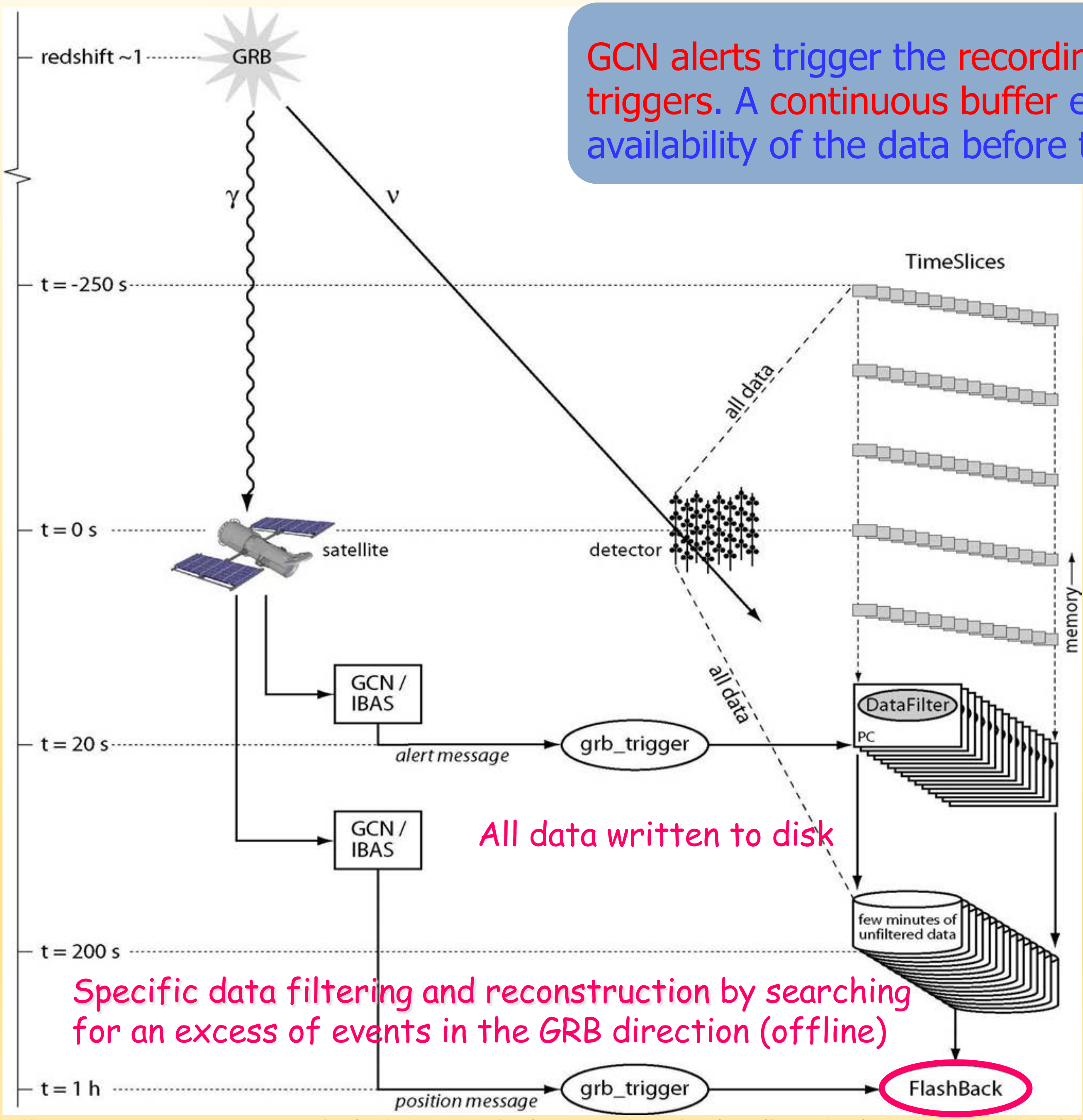
t =-250 s

t = 0 s

t = 20 s

t = 200 s

t = 1 h




Data taking triggered by a satellite (FERMI; SWIFT, INTEGRAL)

All data written to disk

Specific data filtering and reconstruction by searching for an excess of events in the GRB direction (offline)

# ANTARES Multi-messenger program: an example

# search for $\nu_\mu$ from very bright GRB sources

A search was performed for 4 bright GRBs:

GRB080916C, GRB 110918A, GRB 130427A and GRB 130505A)

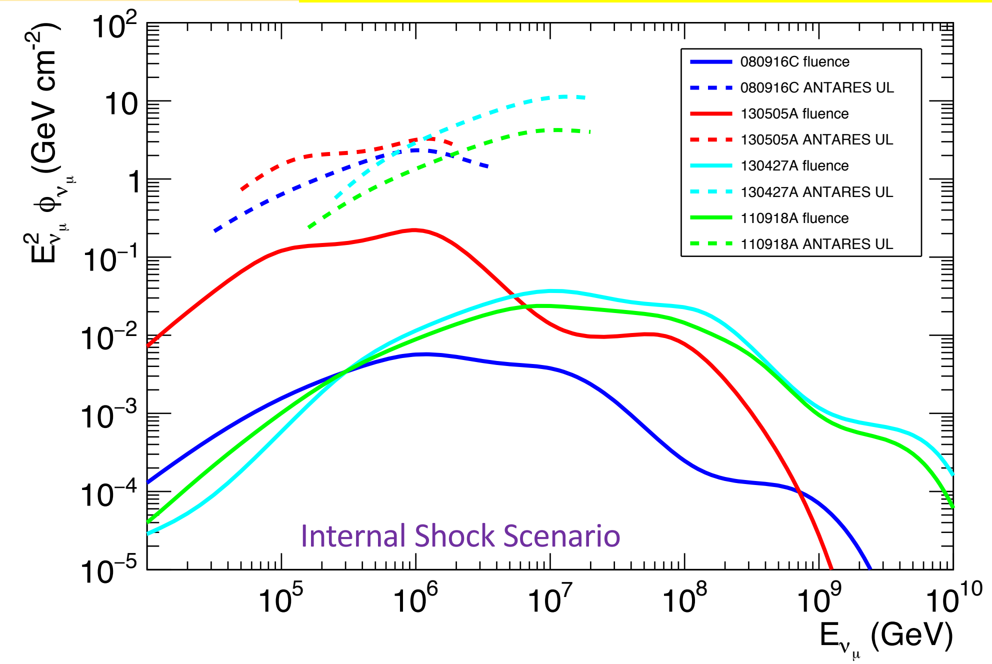
observed between 2008 and 2013.

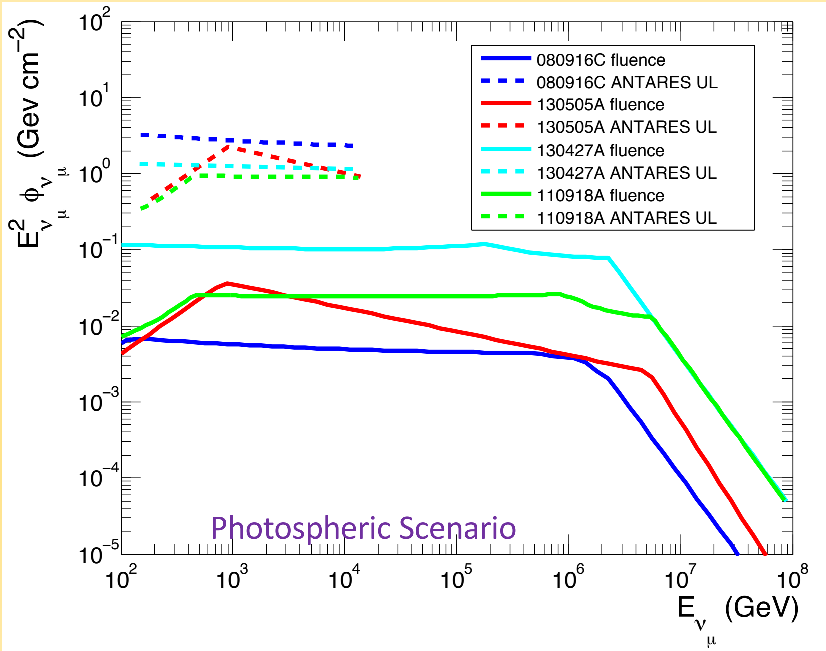
The expected neutrino fluxes evaluated in the framework of:

- the fireball model have with the internal shock scenario ($E_\nu \geq 100TeV$)
- the photospheric scenario ($E_\nu < 10TeV$)

No events have been found: 90% C.L. upper limits to the neutrino fluence.

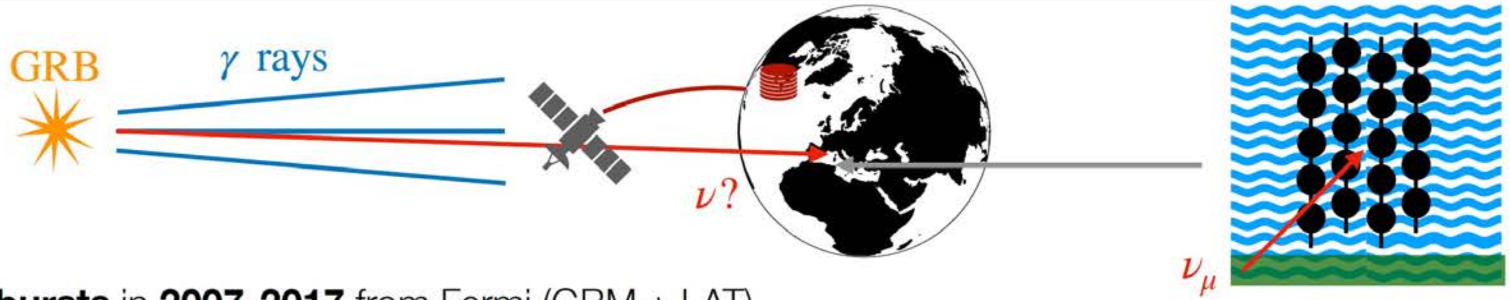
Monthly Notices Royal Astronomical Society (2017) 469 (1): 906-915.



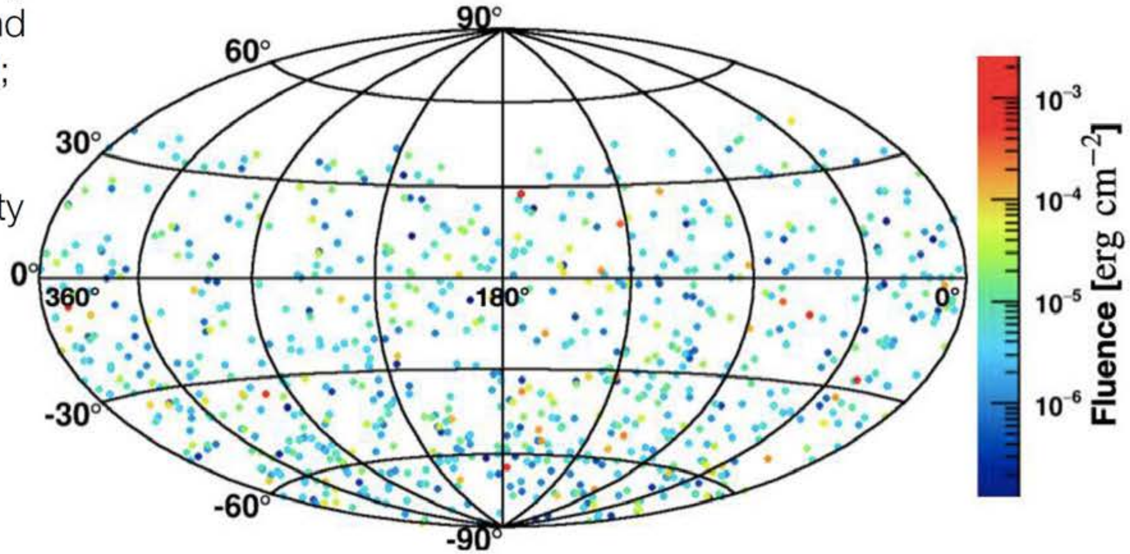
# ANTARES Multi-messenger program
## search for $\nu_\mu$ by stacking long GRB sources (1)

## GRB searches with ANTARES




10 years of ANTARES data

- ★ **Long bursts** in **2007-2017** from Fermi (GBM + LAT), Swift (BAT + XRT + UVOT) catalogs and Konus-Wind GCN (https://gcn.gsfc.nasa.gov/gcn3_archive.html);
- ★ Spectrum is measured;
- ★ T90 (~ duration) is measured;
- ★ Position is measured and satellite angular uncertainty is less than 10 degrees;
- ★ One among fluence and redshift is measured;
- ★ **Below ANTARES horizon at trigger time**;
- ★ ANTARES in Physics run;
- ★ GRBs fully contained is a single ANTARES run.




**784 GRBs**

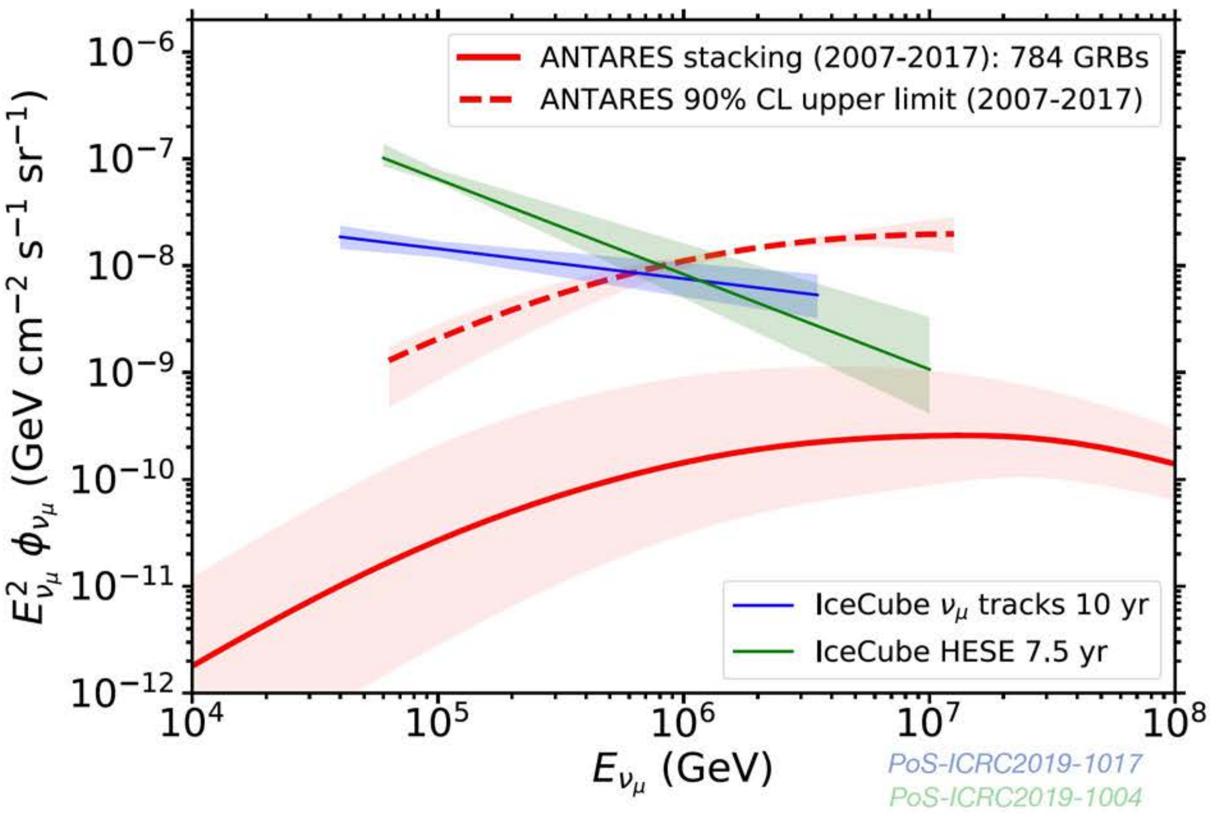
*ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)*

# ANTARES Multi-messenger program

## search for $\nu_\mu$ by stacking long GRB sources (2)

### Results: constrain to HE diffuse neutrino flux

- For a sample size of 784 GRBs the level of systematic error around the 90% C.L. upper limits is of the order of $^{+30}_{-70}\,\%$
- **GRBs are not the main contributors to the observed flux below ~ 1PeV,** within the NeuCosmA model framework with benchmark baryonic loading, $f_p = 10$
- **In the energy region where ANTARES is most sensitive (below 100 TeV), GRBs do not contribute by more than 10%**

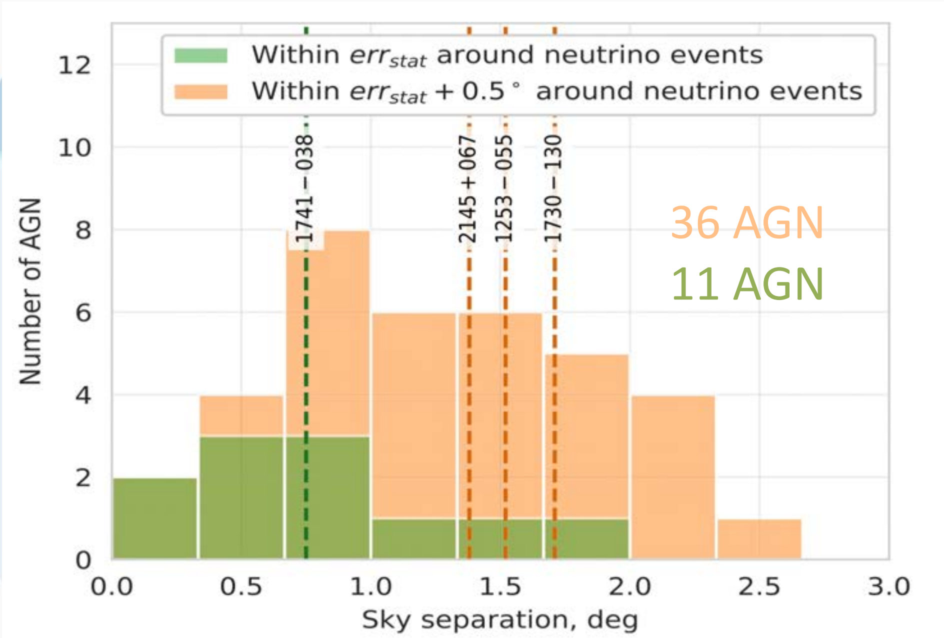


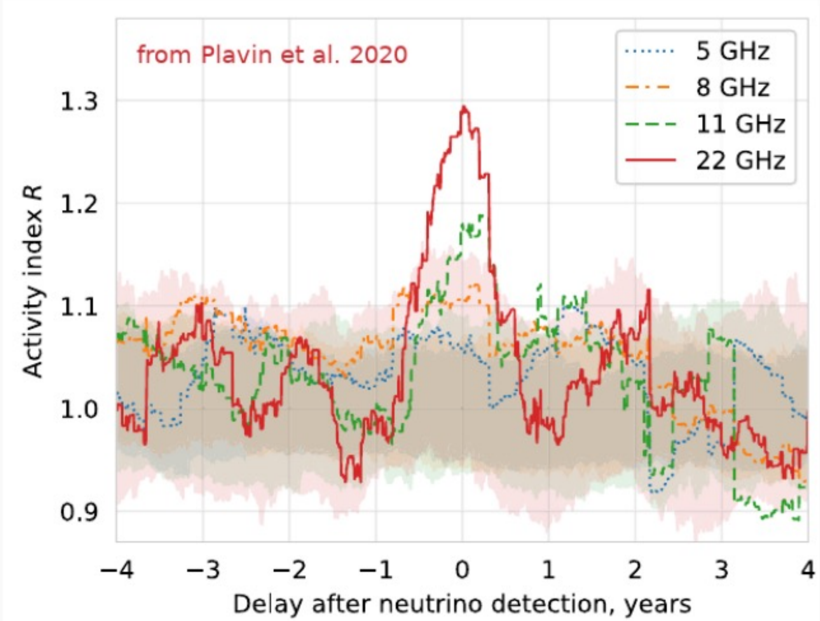

ANTARES Collaboration, MNRAS 500, 5614–5628 (2021)

# IceCube and Radio Blazars

## Recent evidence for Radio Blazars- IC neutrinos association

- Plavin et al. 2020 https://doi.org/10.3847/1538-4357/ab86bd
- Neutrinos: 56 IceCube tracks with E > 200 TeV (33 from EHEA + 23 from HESE, HESEA, MUONT)
- Blazars: 3388 objects selected in the 8 GHz band from VLBI observations (parsec-scale resolution of the AGN core)




**The authors: '…we conclude that AGNs with bright Doppler-boosted jets constitute an important population of neutrino sources'. The search in the ANTARES data is going on …**

# … but also … triggering on Neutrino Telescopes

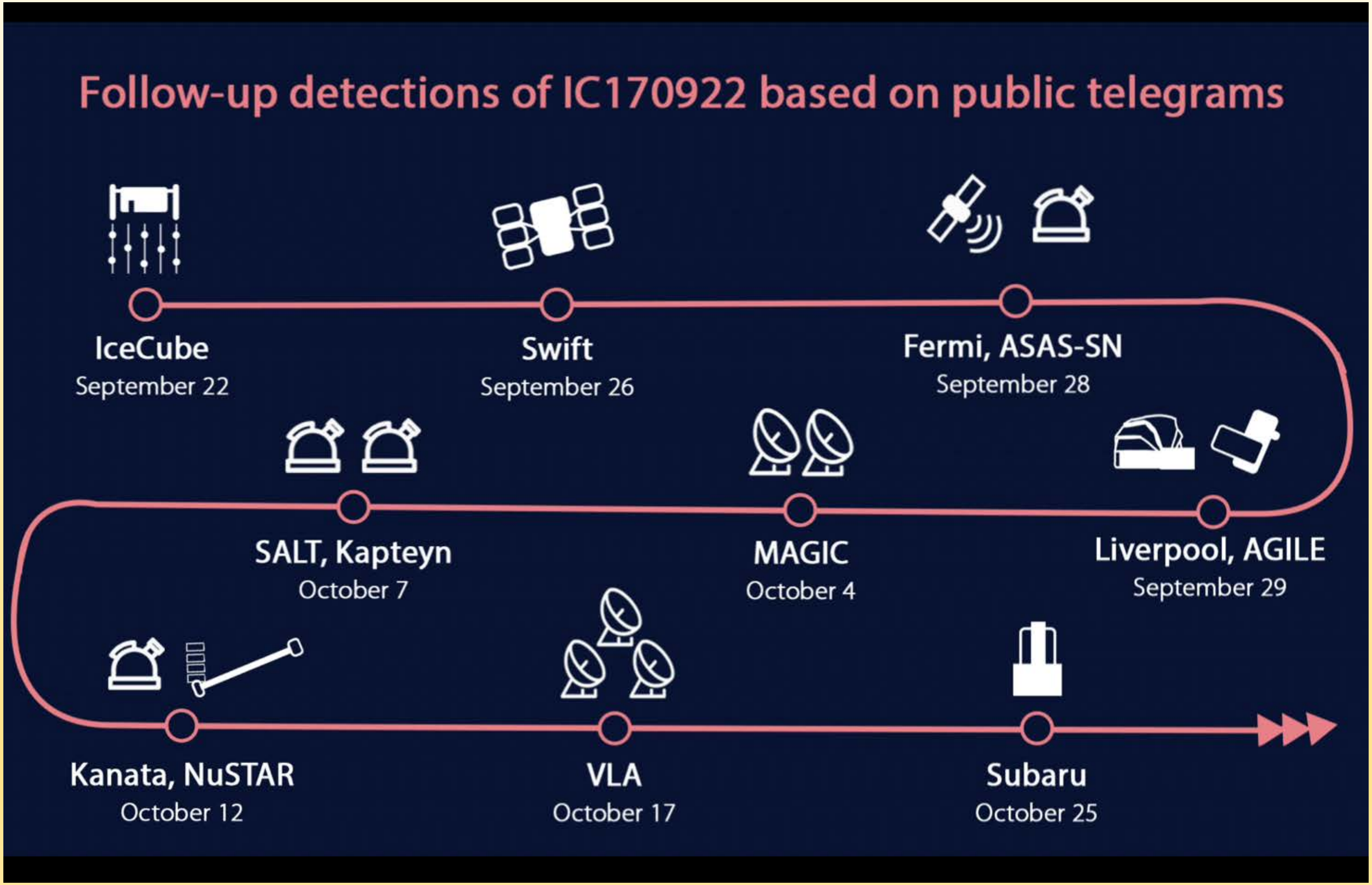
IceCube 170922A very High Energy Event:
Trigger sent to other astrophysical experiments

## IceCube Trigger

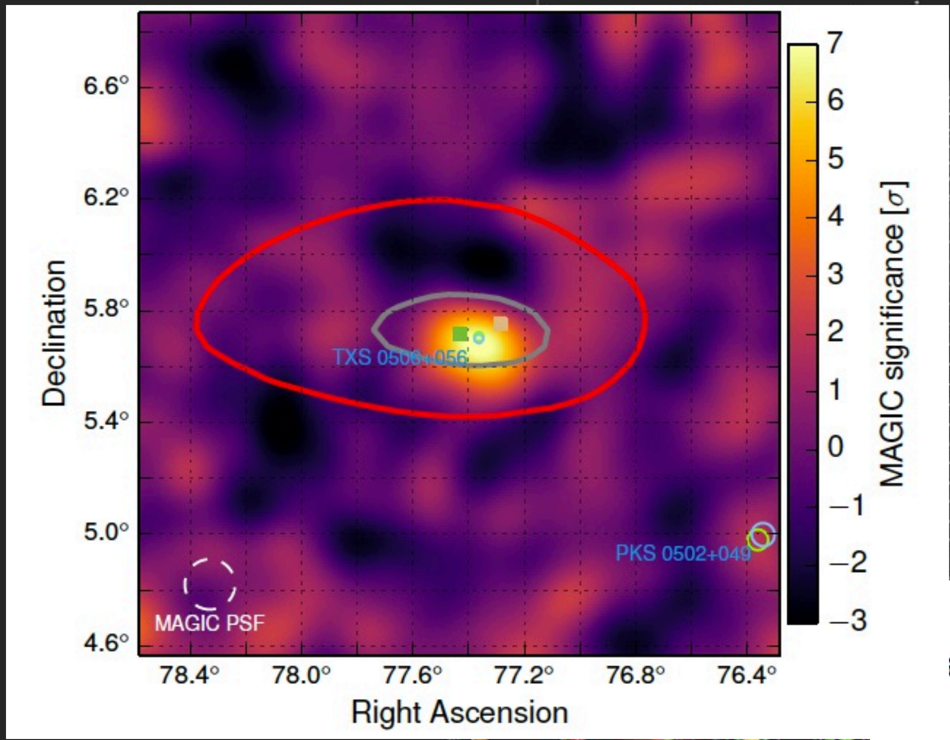
43 seconds after trigger, GCN notice was sent

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
```

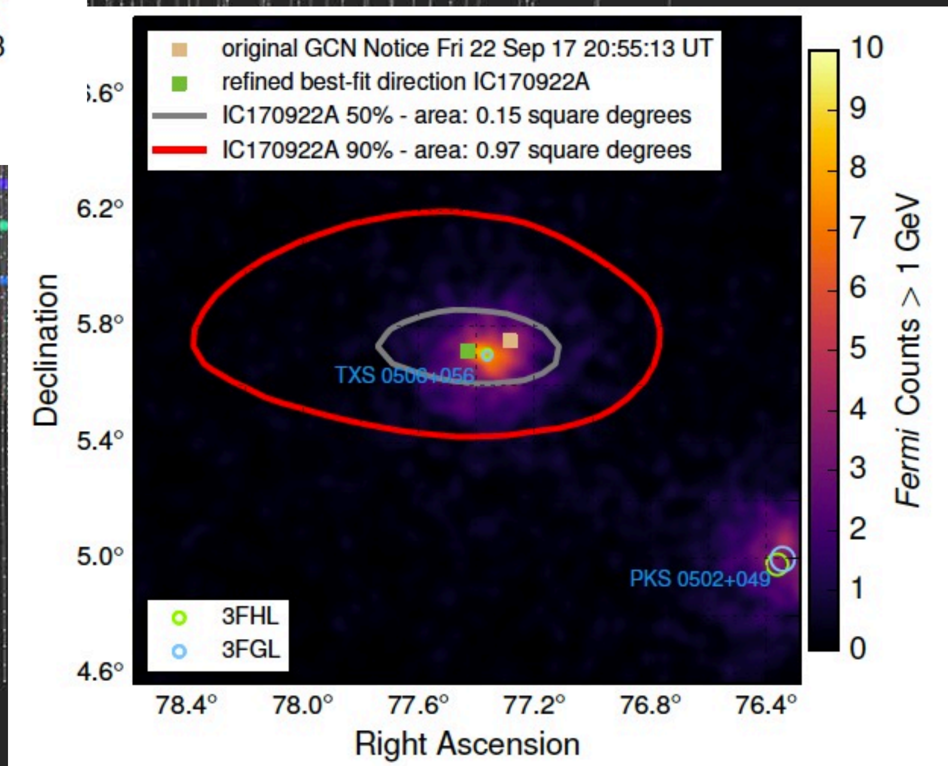
# Triggering on Neutrino Telescopes site



# IceCube 170922



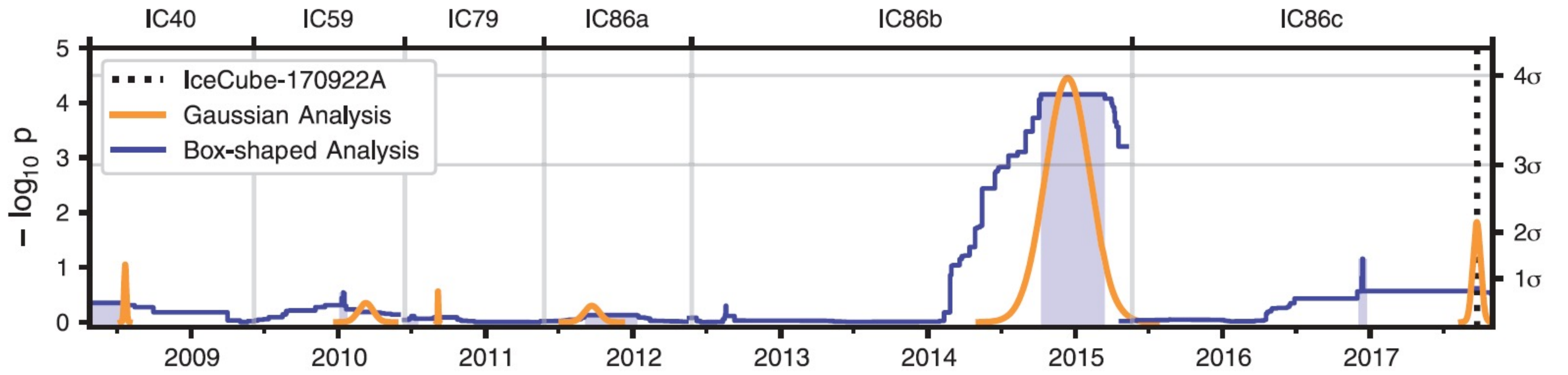

Fermi
detects a flaring
blazar within 0.06°



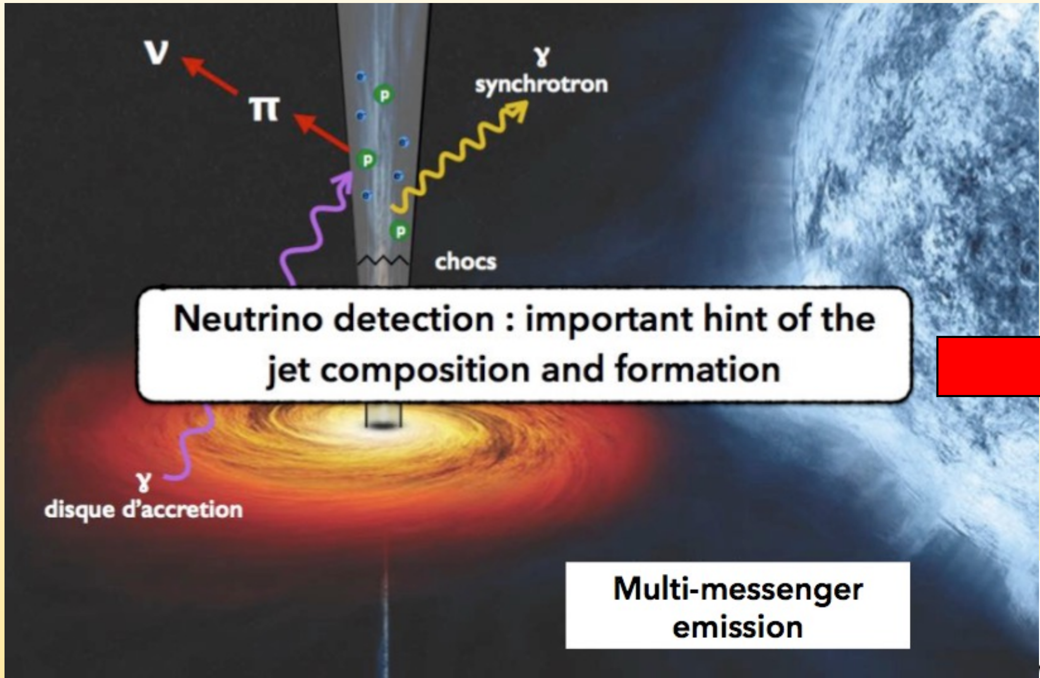

MAGIC
detects emission of
> 100 GeV gammas

# IceCube 170922A coincides with the TXS0506+056 blazar

IceCube investigated **9.5 years of previously collected data** searching for excess emission at the position of the blazar: **found 3.5σ evidence for neutrino emission** from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode. **This suggests that blazars are identifiable sources of the high-energy astrophysical neutrino flux.**



# Multi-messenger astronomy: the ultimate approach




Neutrino detection : important hint of the jet composition and formation

Multi-messenger emission

**Offline**

Time-dependent searches:
- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

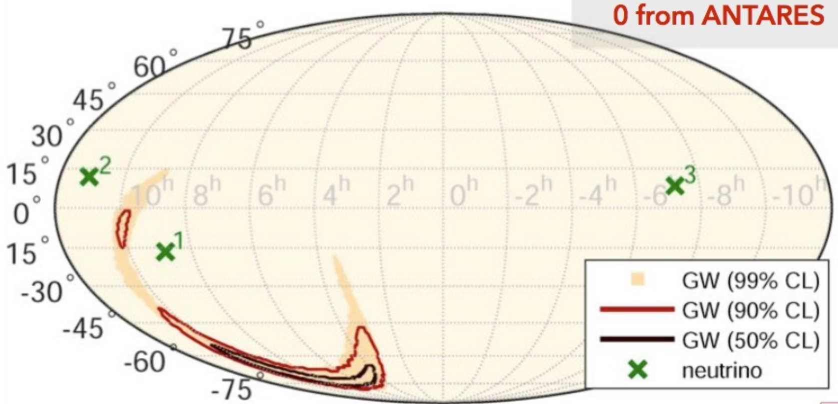
Multi-messenger correlation:
- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH , IceCube HESE

**TAToO**

Real-time analysis:
- TAToO: follow-up of the neutrino alerts with optical telescopes [TAROT, ROTSE, ZADKO, MASTER], X-ray telescope [Swift/XRT], GeV-TeV γ-ray telescopes [HESS] and radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Within ±500 s from GW alert

**3 IceCube candidates**
**0 from ANTARES**



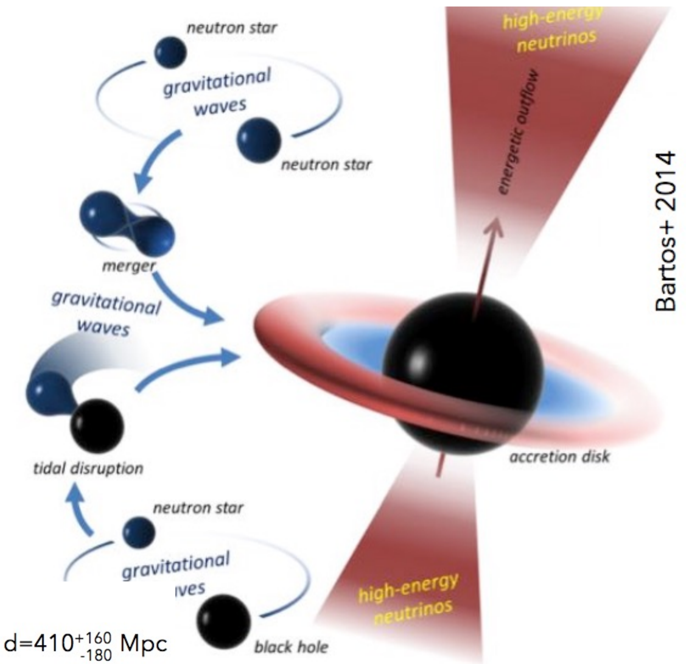

➜ Consistent with the background expectations (4.4 events for IceCube; $10^{-2}$ for ANTARES)

**For BH/NS or NS/NS systems :**

gravitational waves
+ electromagnetic
+ neutrino emission
expected if ejection process with baryonic component

$$E^{ul}_{\nu,tot} = 5.4 \times 10^{51} - 1.3 \times 10^{54}\ \mathrm{erg}$$
$$E^{ul(cutoff)}_{\nu,tot} = 6.6 \times 10^{51} - 3.7 \times 10^{54}\ \mathrm{erg}$$

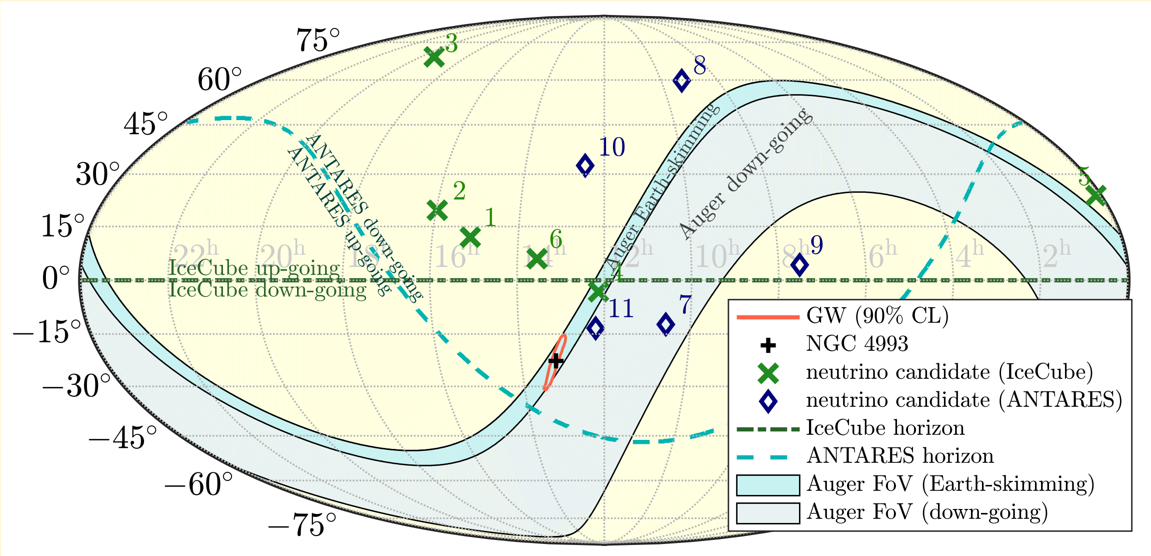
at d=$410^{+160}_{-180}$ Mpc




Bartos+ 2014

# A joint ANTARES-IceCube-LigoSC-Virgo-Auger analysis

## performed as "Neutrino follow-up" of GW170817

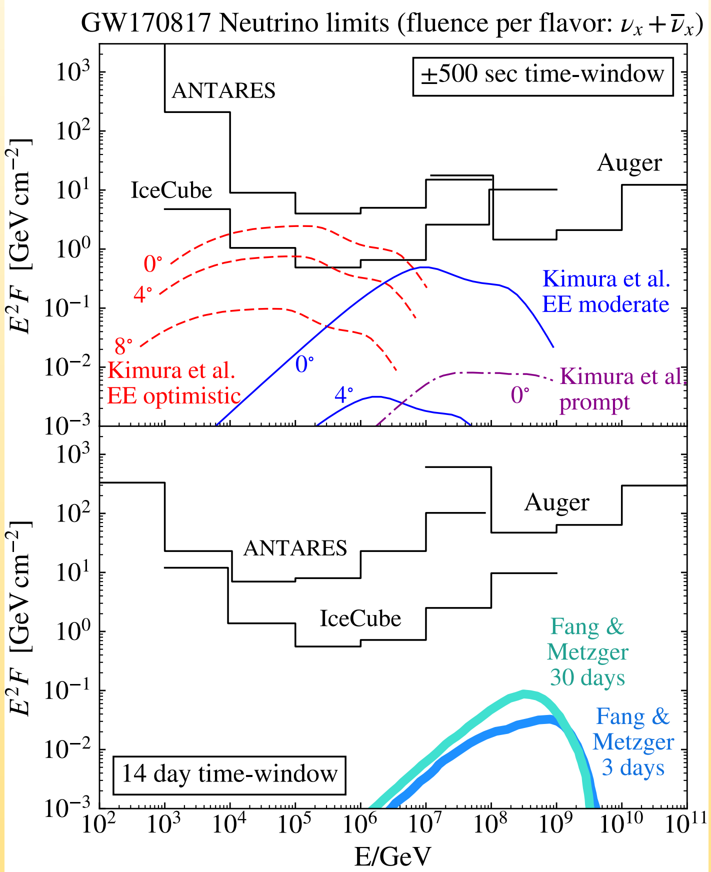



The location of this source was nearly ideal for Auger.
It was well above the horizon for IceCube and ANTARES for prompt observations.
IceCube and ANTARES sensitivity is then limited for neutrinos with $E_\nu < 100$ TeV.

- A **short gamma-ray burst** (GRB) that followed the merger of this binary system was **recorded by the Fermi-GBM** ($E_{iso} \sim 4 \cdot 10^{46}$ erg) and **INTEGRAL.**
- Advanced LIGO and Advanced Virgo observatories reported **GW170817**
- Optical observations allowed the precise localization of binary neutron star inspiral in **NGC4993** at ~**40Mpc**.
- **ANTARES**, **IceCube**, and **Pierre Auger Observatories** searched for high-energy neutrinos from the merger in the **$10^{11}$ eV–$10^{20}$ eV** energy range .
- **IceCube** detector is also sensitive to outbursts of **MeV neutrinos** via a simultaneous increase in all photomultiplier signal rates.

# A joint ANTARES/IceCube/LigoSC/Virgo/Auger analysis performed as "Neutrino follow-up" of GW170817

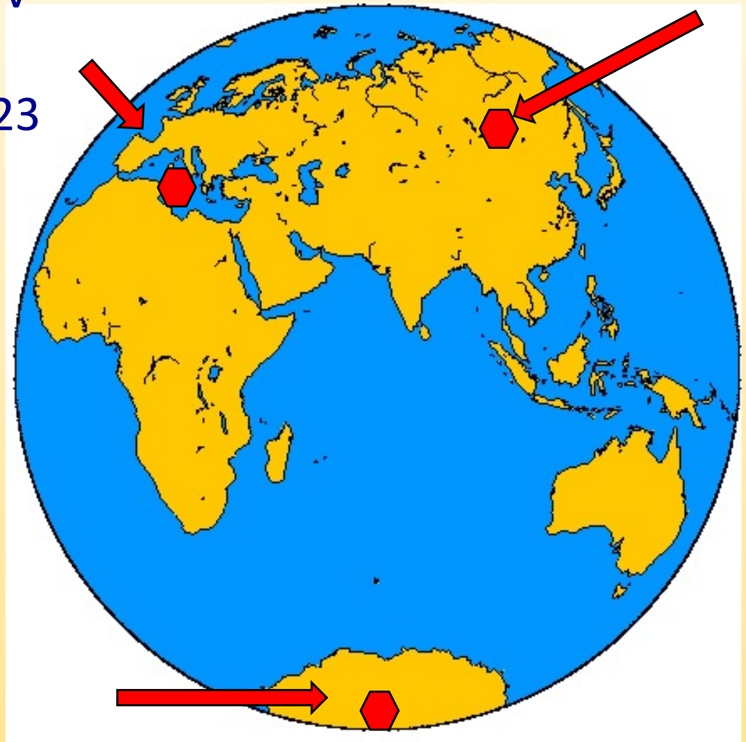
- **No neutrinos** directionally coincident with the source were **detected within ±500 s** around the merger time**.**
- Additionally, **no MeV neutrino burst signal was detected (in IceCube)** ***coincident with the merger*****.**
- In **Pierre Auger Observatory no** inclined showers passing the Earth-skimming selection (**neutrino candidates**) **were found in the time window ±500 s** around the trigger time of GW170817**.**
- **No neutrino found in an extended search in the direction within the 14-day period following the merger.**
- **GRB170817A's** observed **prompt gamma-ray emission**, as well as Fermi-GBM's luminosity constraints for extended gamma-ray emission, are **significantly below typical values for observed short GRBs**. One possible explanation for this is the **off-axis observation of the GRB**.




- The non observation of neutrinos allow to put limits both extended emission (EE) and prompt emission (scaled to a distance of 40 Mpc): limits are shown for the case of on-axis viewing angle (0) and selected off-axis angles to indicate the dependence on this parameter.

# The global approach to next generation ν Telescopes

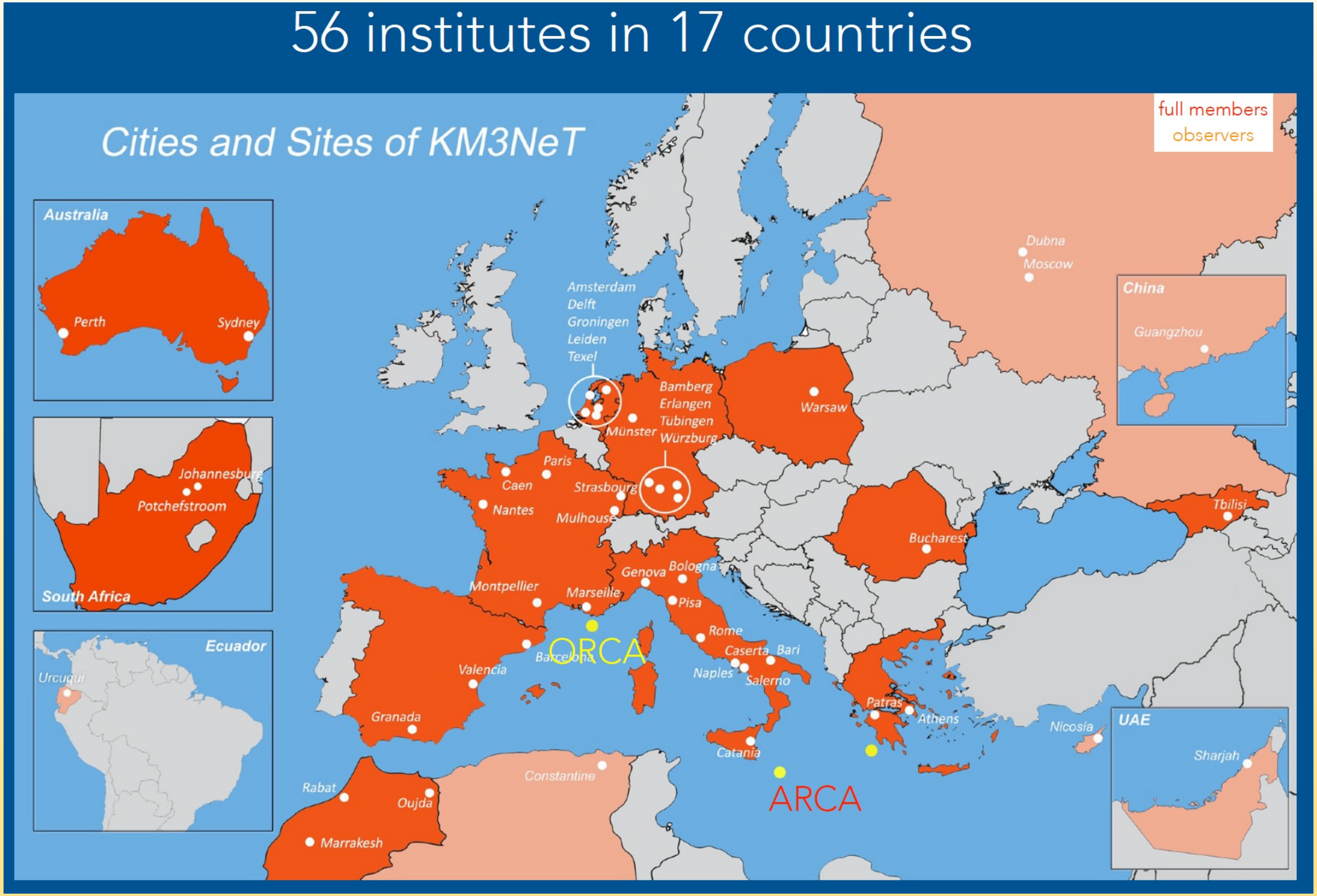
KM3neT/ARCA
optimized ~1.4 km$^3$ → >1 TeV
(1-5 km$^3$)
construction 2015(18) – 2023
Deep – Sea water
high angular resolution
depth 2.7 – 3.3 km
no veto available



GVD
optimized ~0.4 km$^3$ → >10 TeV
(1.5 km$^3$)
construction 2015 – 2024
Lake fresh water
good angular resolution
depth 0.7 – 1.2 km
no veto available

IceCube-Gen2
optimized ~ 1 km$^3$ → >1 TeV
~ 10 km$^3$ → > 30 TeV
Operating 2021 – 2032
Ice (scattering, medium homogeneity, …)
Moderate angular resolution
Depth 1.4 – 2.7 km
Surface Veto !!!

# KM3NeT Collaboration

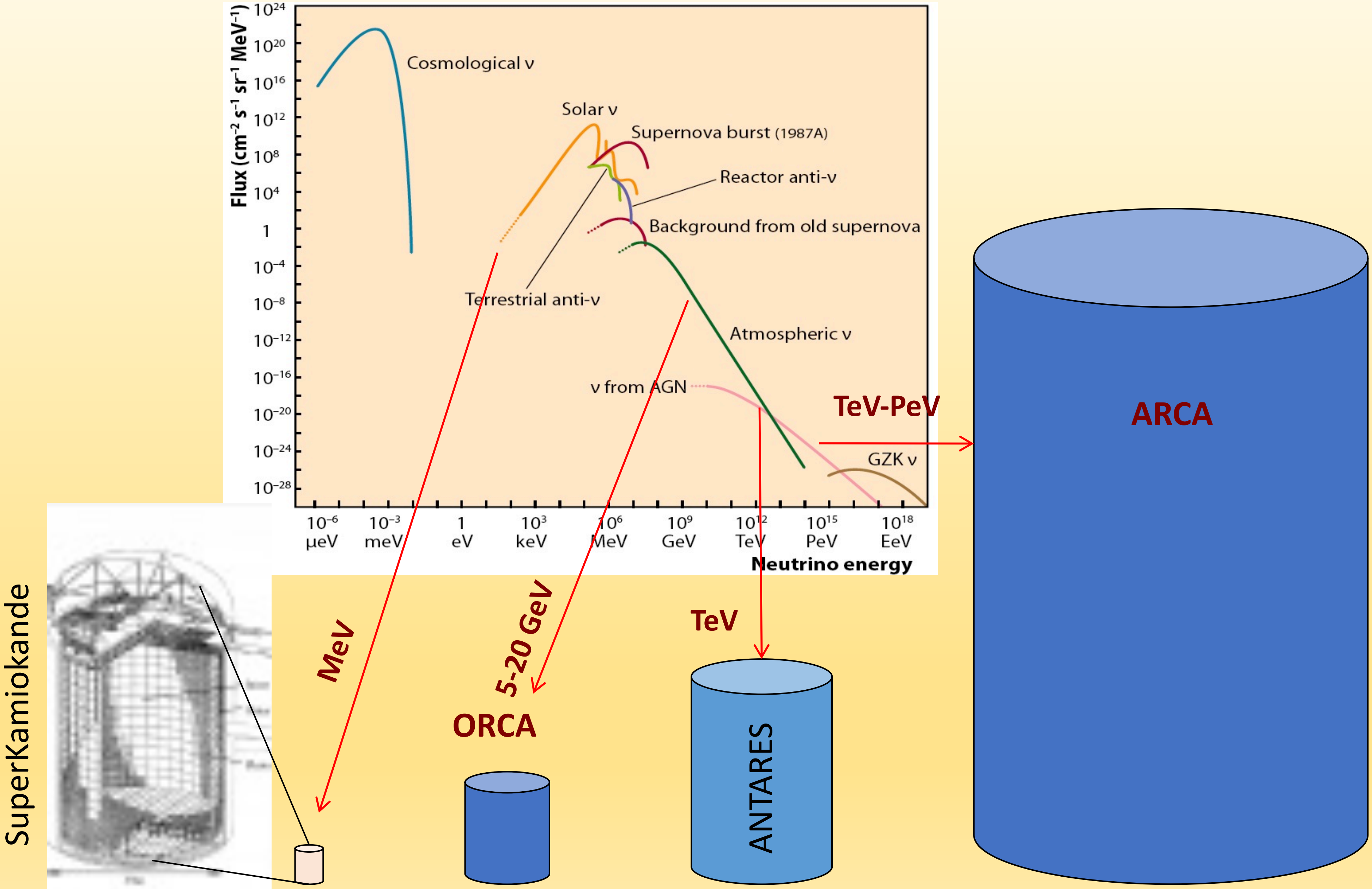



1 collaboration, 1 technology 👉 2 detectors:

**ORCA (Oscillation Research with Cosmic in the Abyss)**

**ARCA (Astroparticle Research with Cosmics in the Abyss)**

# … yesterday, today, tomorrow …



# KM3NeT technology

The basic elements:

- Optical sensors 👉 DOMs (Digital Optical Module)
- Strings 👉 DU (Detection Unit)
- Seafloor network 👉 Electro-optical cables and JBs (Junction Boxes)

DOM

It is a 17" glass sphere with inside:

- 31 3" PMTs (photocathode aerea ≃ 3 × 10" PMTs)
- LED and Piezo
- Front-end electronics -> FPGA

all data to shore

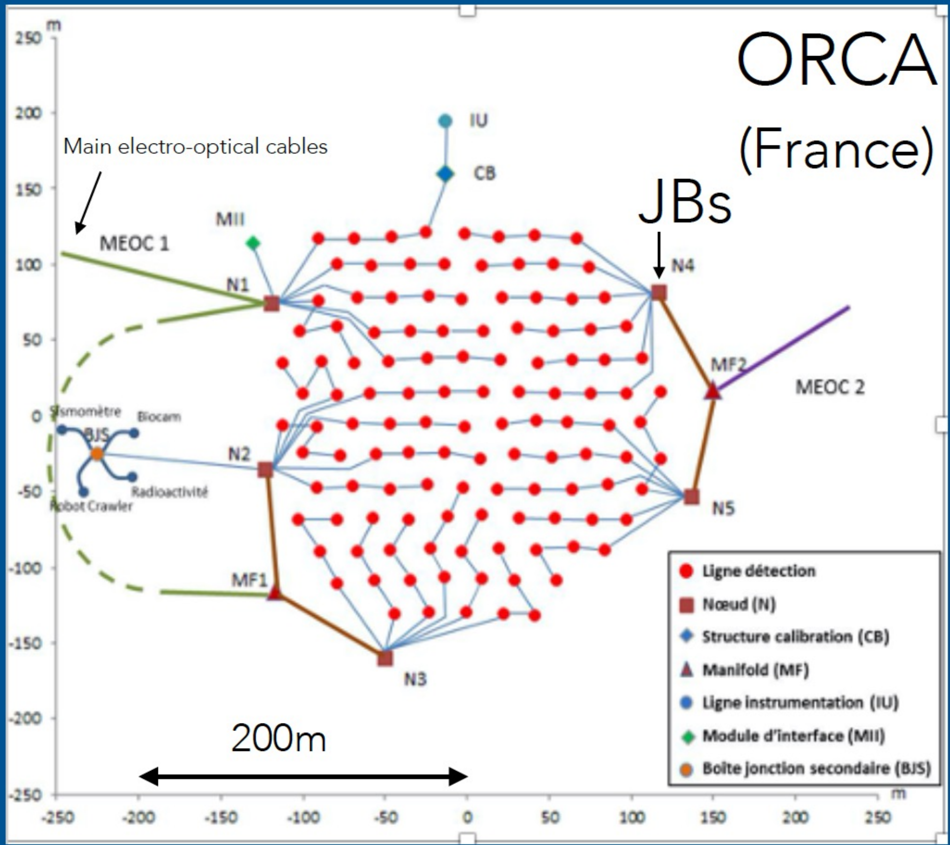


DU

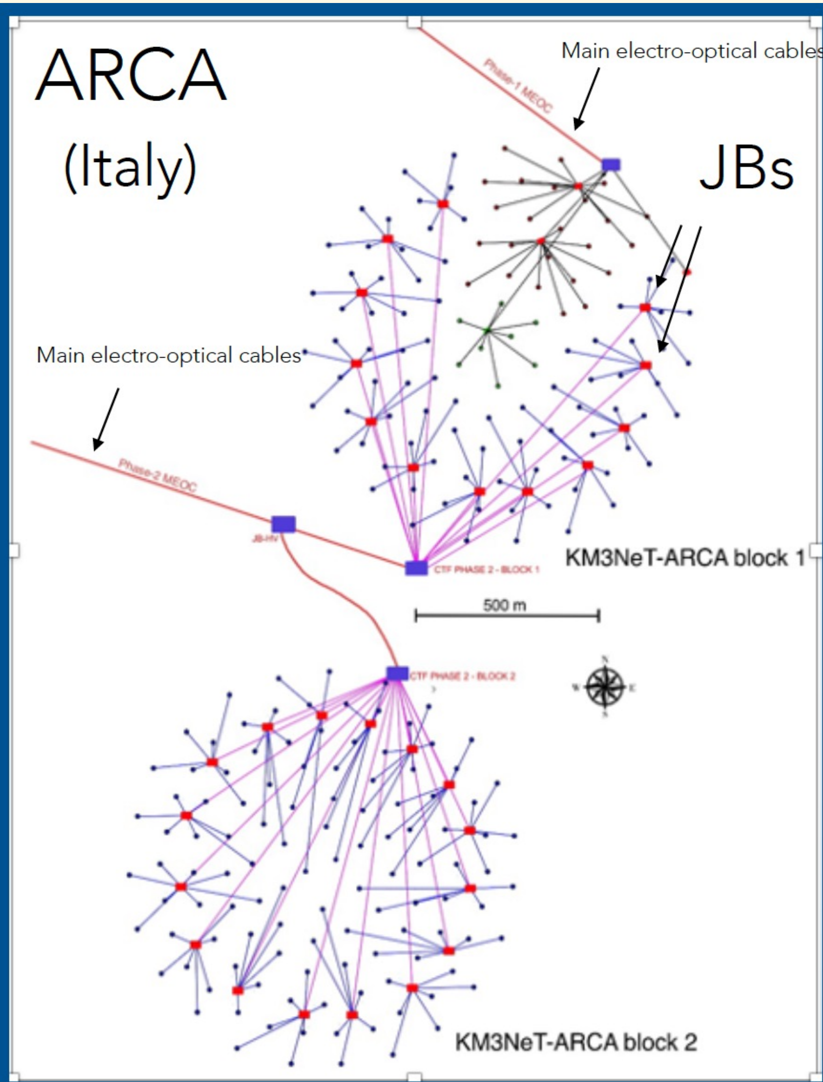
18 DOMs in a DU

JB

# KM3NeT Building Blocks

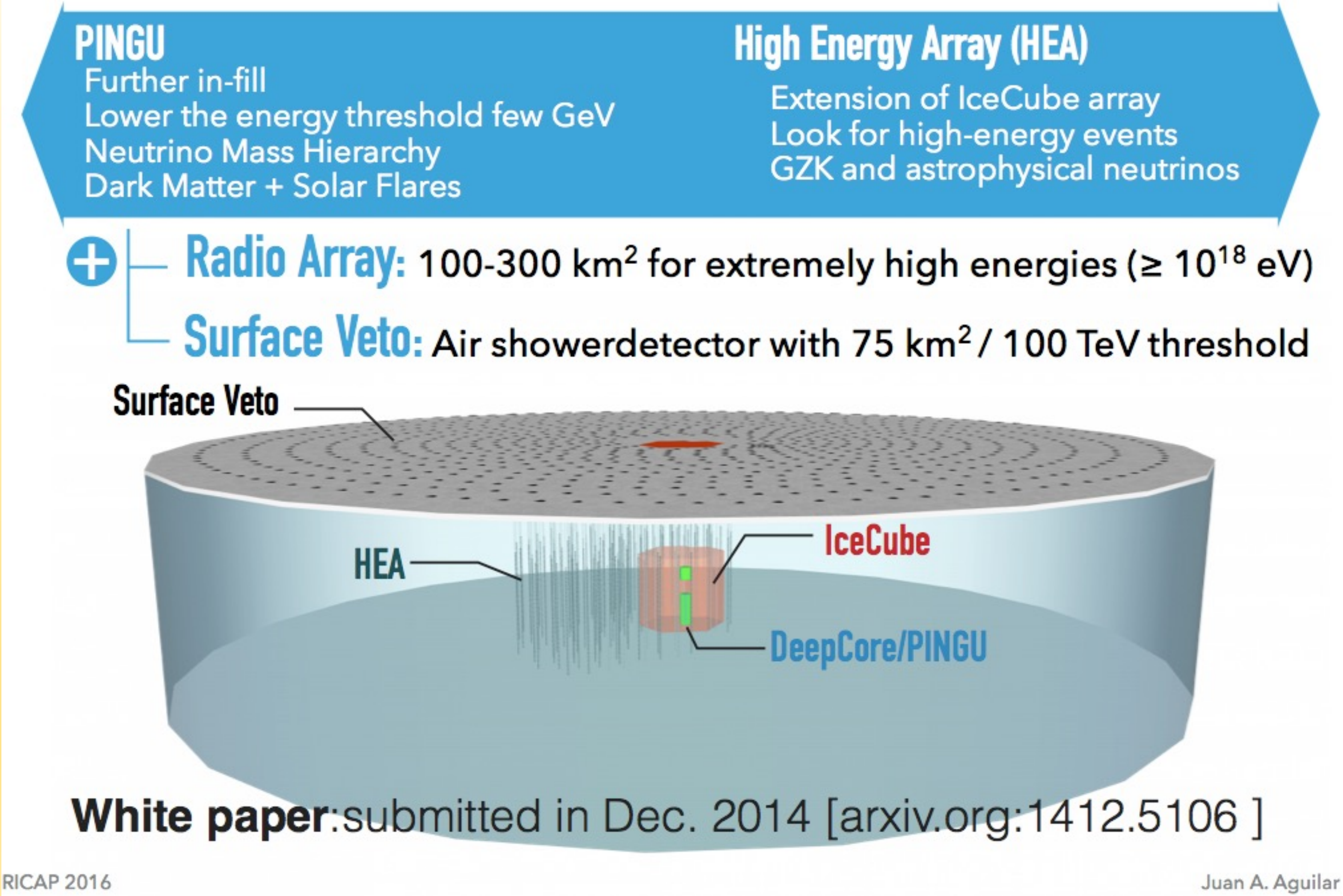



**ORCA is composed of 1 building block of 115 DUs** each with 20 m DU interspacing and 9m inter DOM spacing (7 Mton)



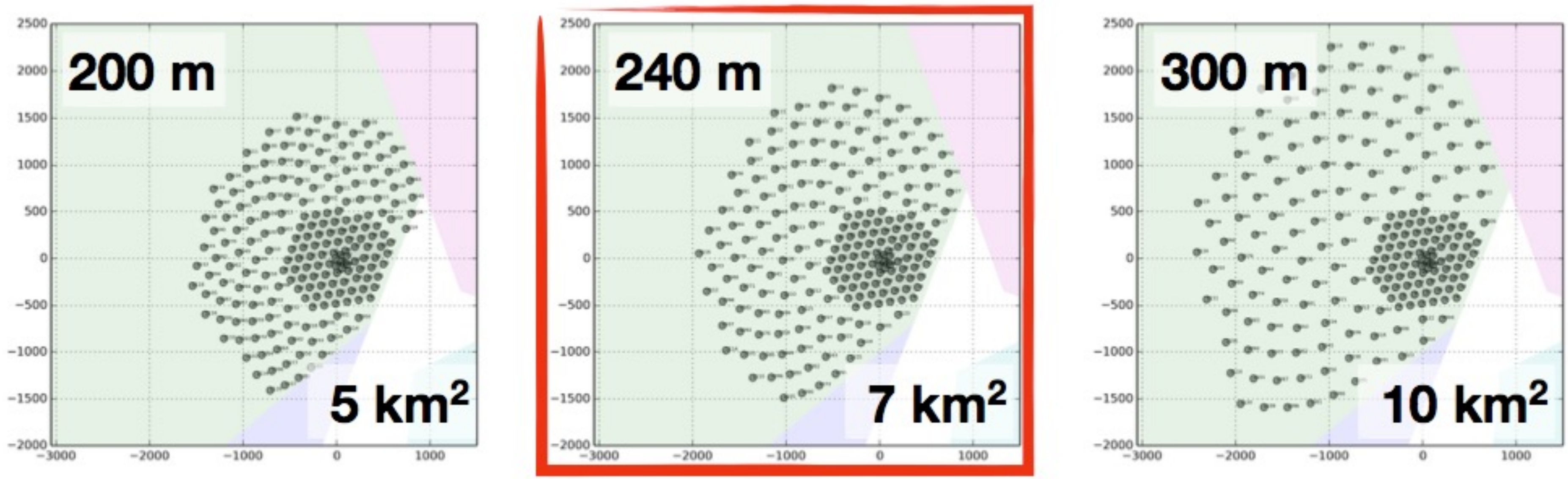

**ARCA is composed of 2 building blocks of 115 DUs** each with 90 m DU interspacing and 36m inter DOM spacing (0.5 km3=500Mton/block)

# at the South Pole



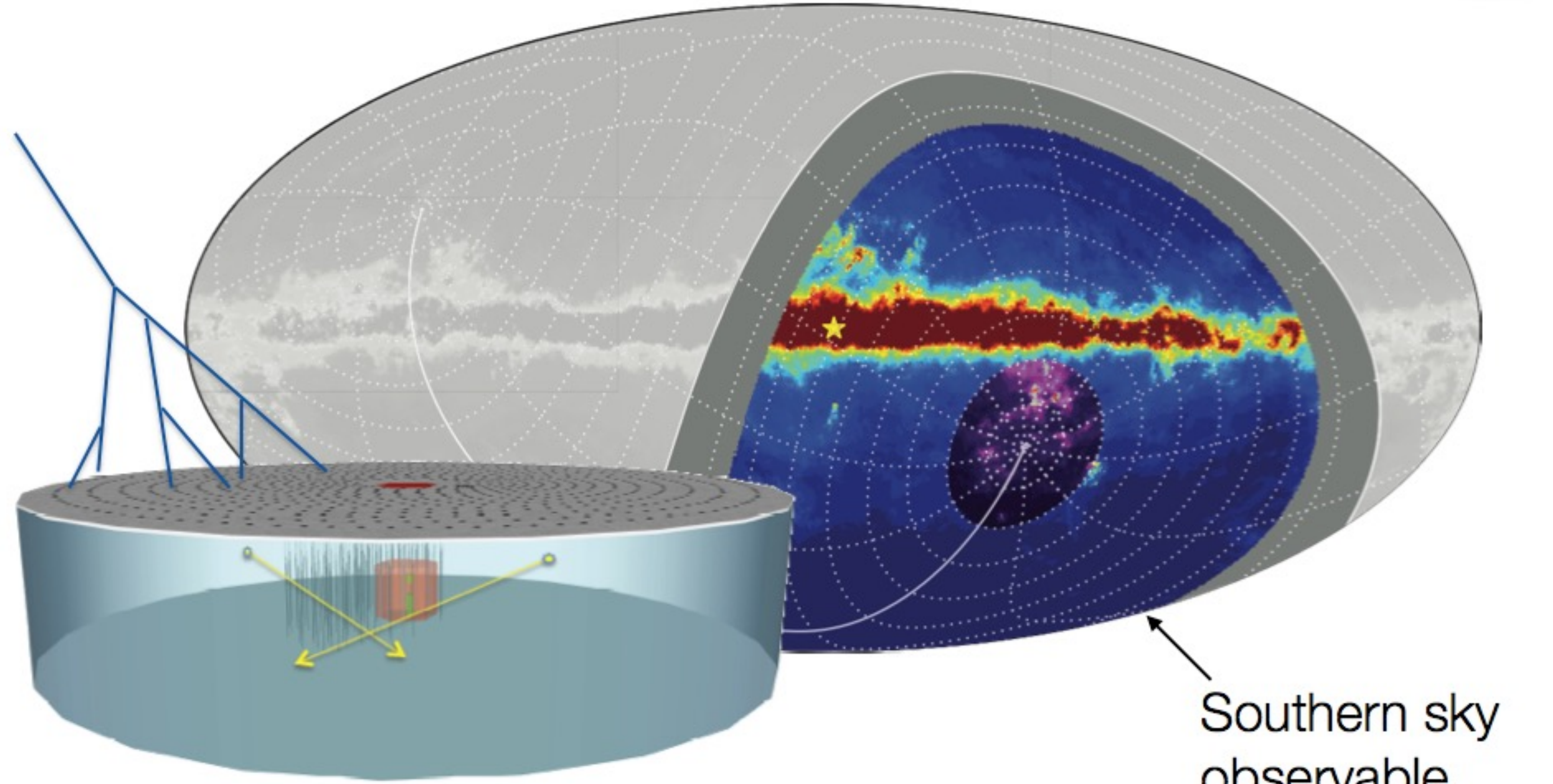
# IceCube Gen2

- Several layouts under evaluation
- Example: "Sunflower" geometry with different string spacings




- ~120 new strings, 80 DOMs per string, instrumented over 1.25 km
- ~10 x IC volume for contained event analysis above 200 TeV

# a unique facility: vetoing downgoing events

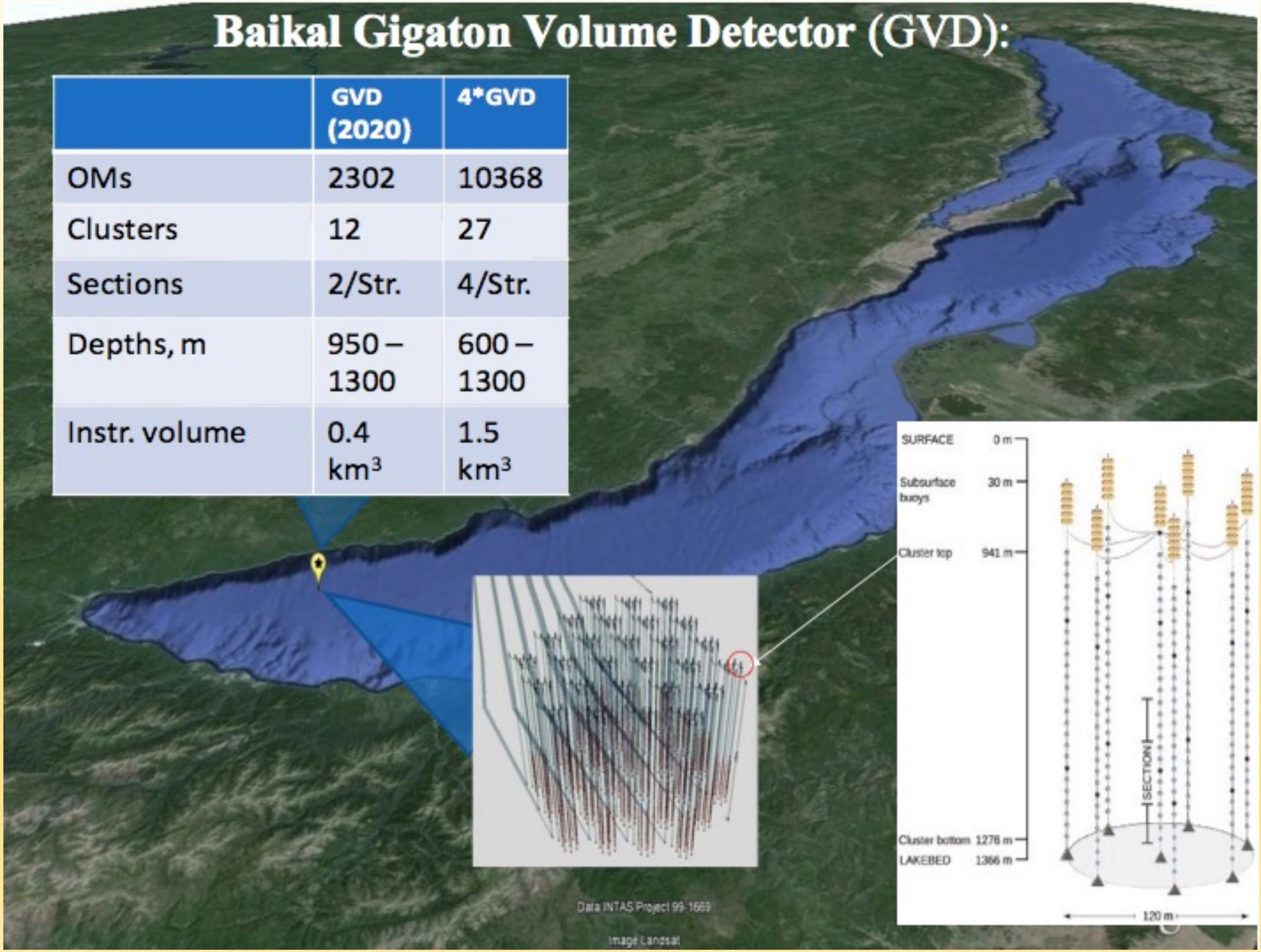



**Potential gain for e.g. 75 km² veto:**

~2x number of PeV tracks

~2x precision in spectral index

# The Baikal – GVD project



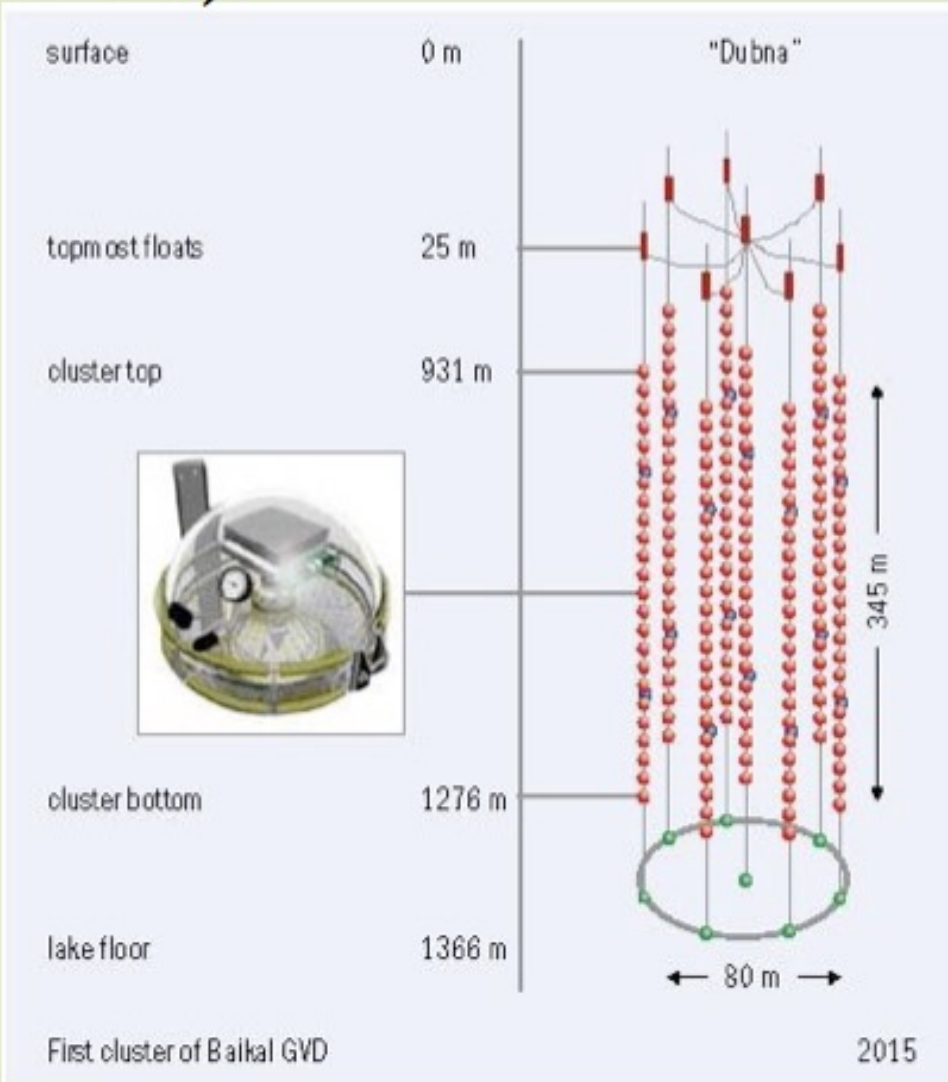

| | GVD (2020) | 4*GVD |
|---|---|---|
| OMs | 2302 | 10368 |
| Clusters | 12 | 27 |
| Sections | 2/Str. | 4/Str. |
| Depths, m | 950 – 1300 | 600 – 1300 |
| Instr. volume | 0.4 km³ | 1.5 km³ |

# The Baikal – GVD project, the prototype

## First Demonstration Cluster "DUBNA" (April 2015)

- 192 OMs at 8 Strings 2×12 OMs per String.
- Acoustic Positioning System
- Instrumentation String for environment monitoring
- LED beacon for inter-string time calibration

**Active depth 950 – 1300 m**
**Instrumented volume 1.7 Mt**



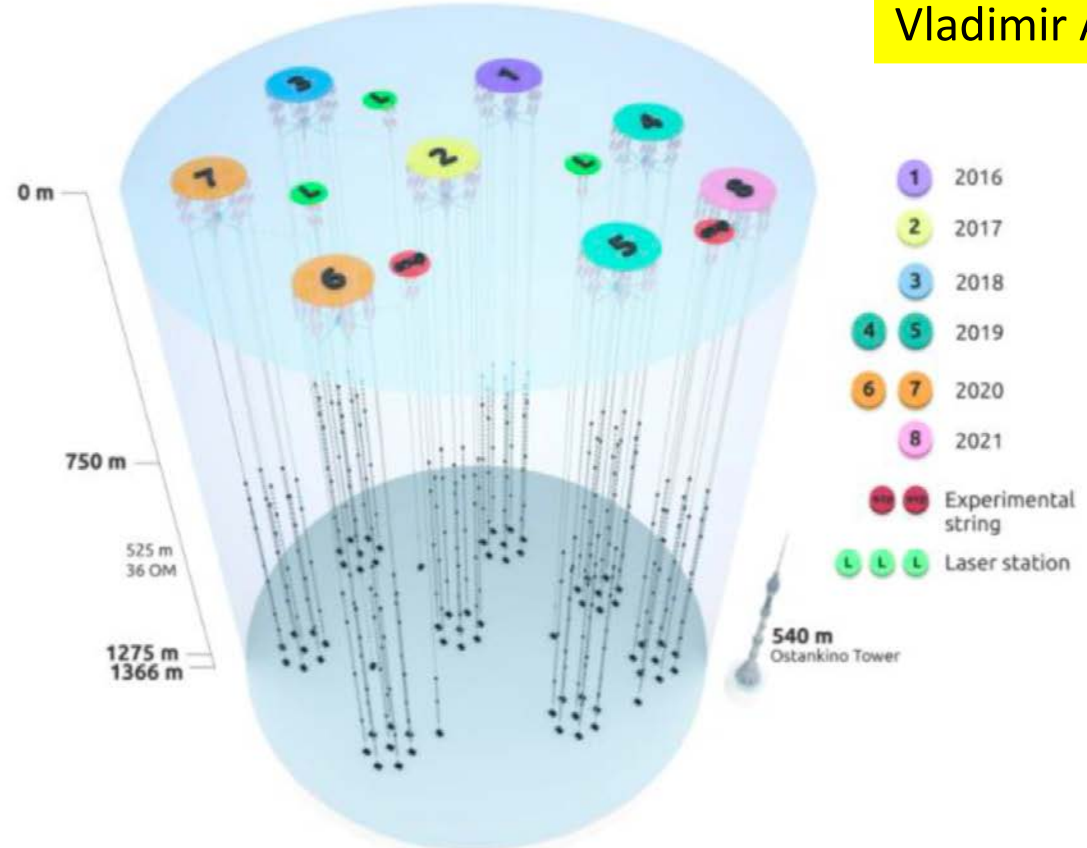

Vladimir Aynutdinov

# The Baikal – GVD project time schedule

## Baikal-GVD construction status and schedule

Status 2021: 8 clusters, 3 laser stations, experimental strings

Vladimir Aynutdinov – VLVnT 2021

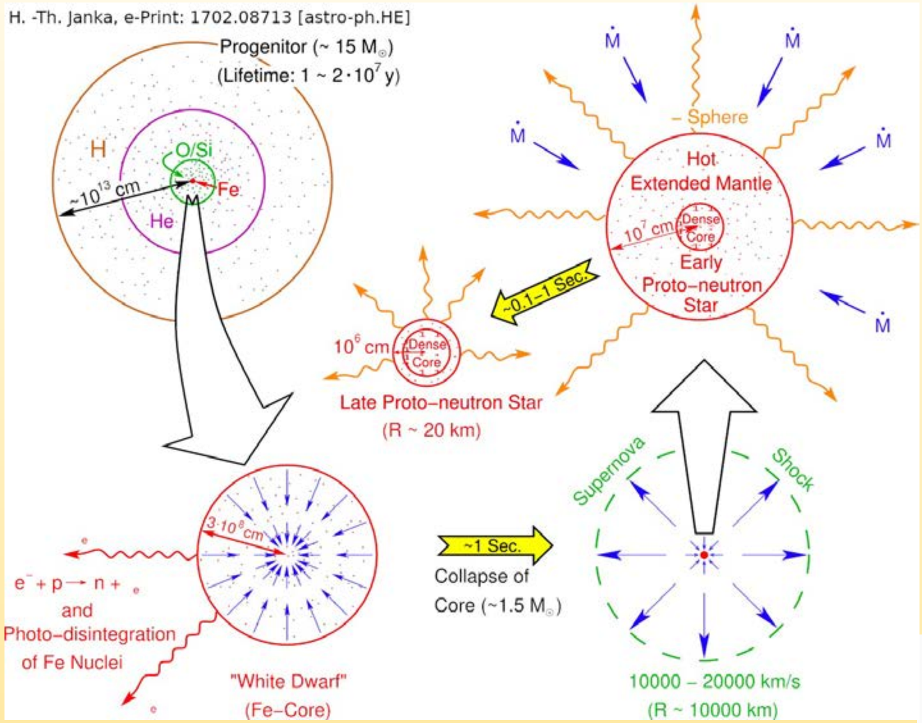


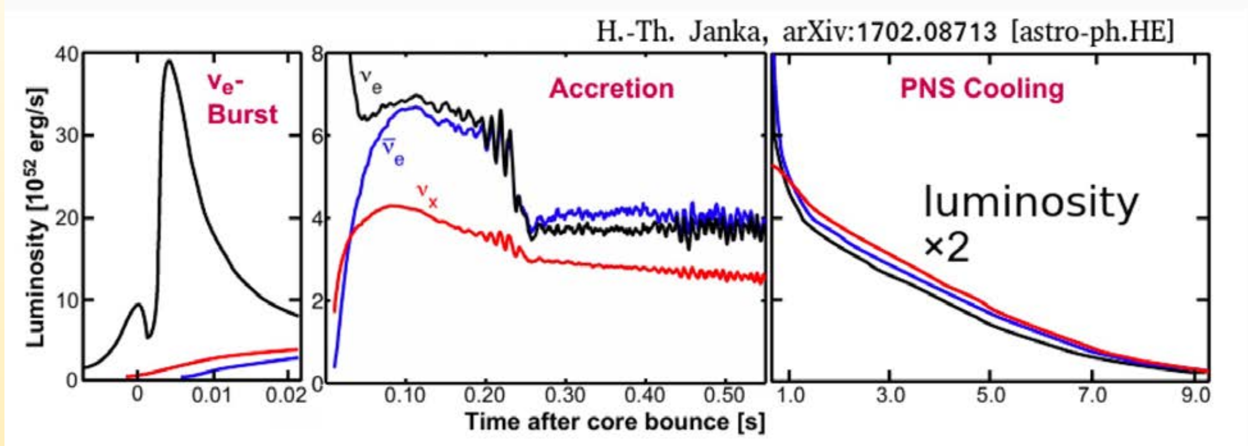

Deployment schedule

| Year | Number of clusters | Number of OMs |
|---|---|---|
| 2016 | 1 | 288 |
| 2017 | 2 | 576 |
| 2018 | 3 | 864 |
| 2019 | 5 | 1440 |
| 2020 | 7 | 2016 |
| 2021 | 8 | 2304 |
| 2022 | 10 | 2880 |
| 2023 | 12 | 3456 |
| 2024 | 14 | 4032 |

Effective volume 2021: 0.40 $km^3$ (cascade mode)

# KM3NeT – sensitivity to CCSN




- CCSN:
- Explosive phenomena ending the life of massive stars with ~$10^{53}$ erg energy release
- 99% of gravitational energy goes into low energy ν (~10 MeV) when optically thick (hours after observ.)
- Expected near CCSN ~1.5 per century

Inverse beta decay (IBD)

$\overline{\nu}_e + p \to n + e^+ \quad (E_e \simeq E_\nu - 1.3\,\text{MeV})$

Elastic scattering on electrons (EES)

$\nu + e \to \nu + e$

CC interaction with oxygen

$\nu_e + {}^{16}\text{O} \to e^- + {}^{16}\text{F}$ (min. 15 MeV)

$\overline{\nu}_e + {}^{16}\text{O} \to e^+ + {}^{16}\text{N}$ (min. 11 MeV)

+ de-excitation $\gamma$s

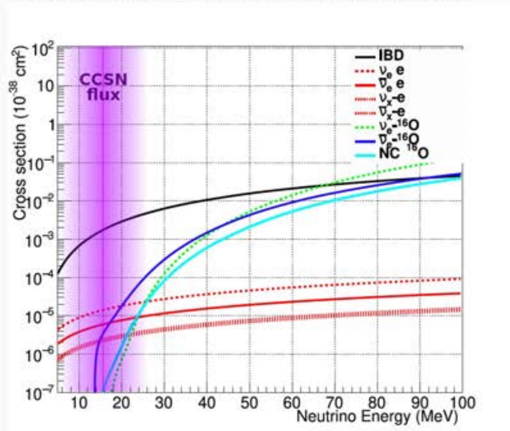
*NC interaction with oxygen*

$\nu + {}^{16}\text{O} \to \nu + {}^{16}\text{O}^*$

only de-excitation $\gamma$s.

Only outgoing leptons are considered (de-excitation $\gamma$s are neglected).

Cross-sections (from SNOwGLoBES):




IBD is the dominant process (97%): larger cross section + efficient $\nu \to e^+$ energy transfer.

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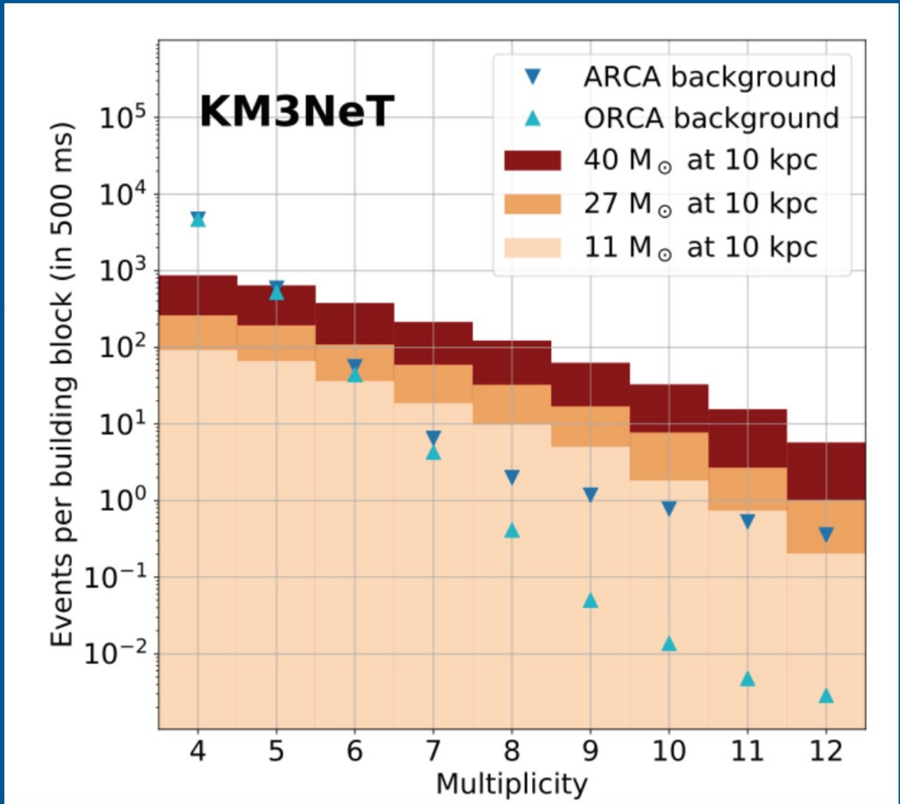
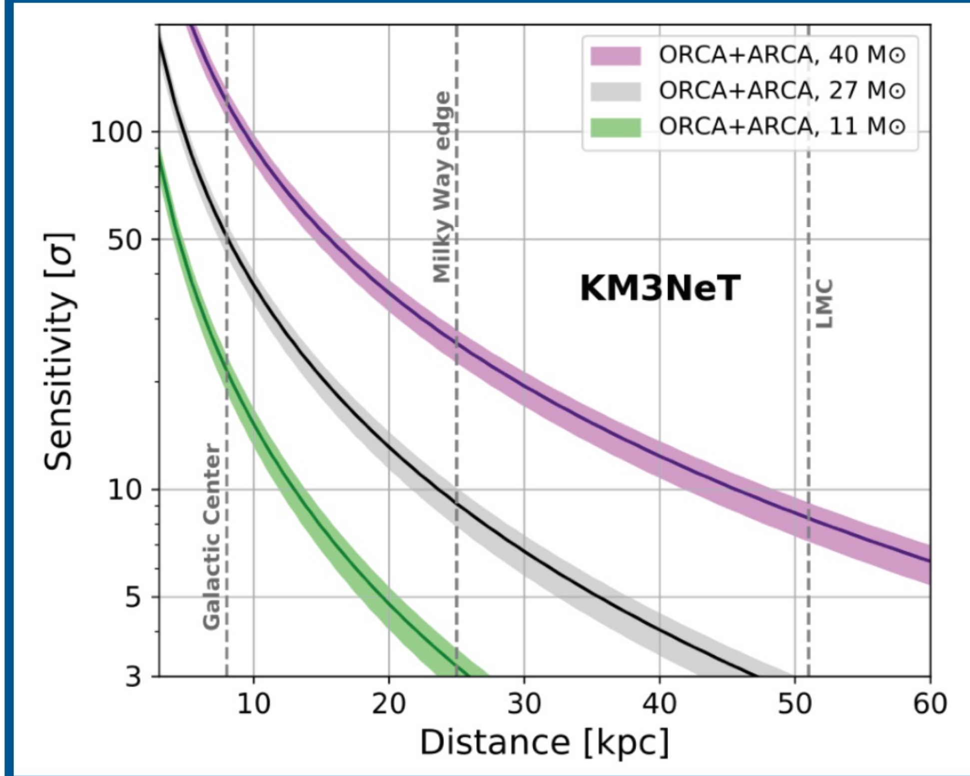



>5σ for ARCA+ORCA for 27M⊙ at a distance <25kpc

A trigger for CCSN already implemented
Integrated in SNEWS

# Summary

- **Astrophysical neutrino fluxes identified and measured**
- **The quest for point-like sources is going on**
- **Multimessenger-efforts:**
    - **search for time-space coincidences**
        - Transient sources offer lower background conditions
    - **H.E.C.R., gamma, neutrino connection**
    - **Better understanding on the acceleration mechanisms and the nature of sources (hadronic-leptonic)**
- **New generation Neutrino Telescopes soon coming in operation**

# Multi-messenger GW-ν sensitivity

For the LIGO-VIRGO - ANTARES detectors:

For **binary neutron star systems** of (1.35-1.35) $M_{Sun}$
and **black hole-neutron star systems** of (5-1.35) $M_{Sun}$
typical distance limits are **5Mpc and 10Mpc** respectively.

For the **sine-Gaussian waveforms with $E_{GW} = 10^{-2} M_{sun} c^2$** we find typical distance limits between **5 - 17Mpc** in the **low-frequency band** and of order **1Mpc** in the **high-frequency band**.

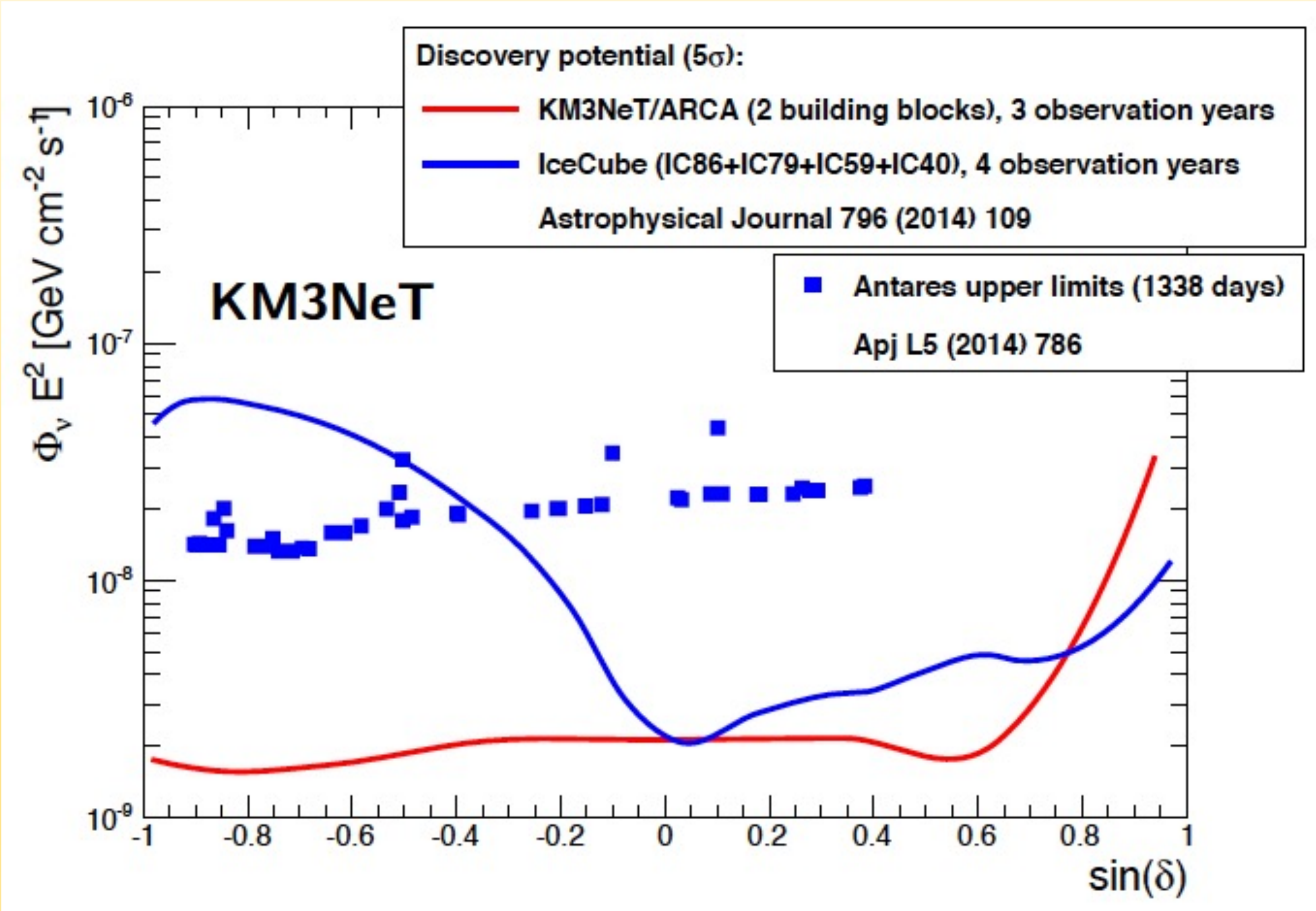
For other $E_{GW}$ the limits scale as $D_{90\%} \propto (E_{GW} / 10^{-2} M_{Sun} c^2)^{1/2}$

→ $E_{GW} = 10^{-8} M_{Sun} c^2$ (typical for CCSN) a signal would only be observable from a Galactic source.

# ARCA (Phase 2) discovery potential for point-like sources

Hypothesis:

- Neutrino spectra ~ $E_\nu^{-2}$.
- 3 years observation time



# KM3NeT – ORCA sensitivity to NMH

- Time dependence of the KM3NeT sensitivity
- ORCA Mass Hierarch determination significance for $\delta_{CP} = 0°$